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Technical Report 145

CATHODIC PROTECTION STUDIES

21 July 1961

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U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

ASTIA

CATHODIC PROTECTION STUDIES

Y-R007-08-901

Type B Final Report

by

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OBJECT OF TASK

To develop satisfactory methods for employing cathodic protection to prevent or inhibit the corrosion of steel equipment under BuDocks cognizance, such as floating drydocks, dredges, crane pontoons, and barges. Methods include the use of direct-current generators, rectifiers, and sacrificial anodes of magnesium and zinc.

ABSTRACT

A seven-section floating drydock was placed under cathodic protection in order to study the interaction between several hulls in a single system and to provide a protracted study of the effectiveness of cathodic protection. The feasibility of using a single power source for many hulls and the practicability of employing automatic control were investigated. The durability of the component materials in the system was observed.

It was concluded that galvanic and impressed current systems are equally effective in reducing corrosion. The choice between them, or between different anode materials is largely a question of the specific application. A combination of cathodic protection and floating inhibitor in a ballast tank provides essentially 100-percent protection. Only two underwater coating systems were considered as having performed satisfactorily. A single rectifier supplied sufficient power for the seven-section drydock, plus an AFDL and three YR-class drydocks. Automatic control systems were successful in maintaining hull polarities within an acceptable range.

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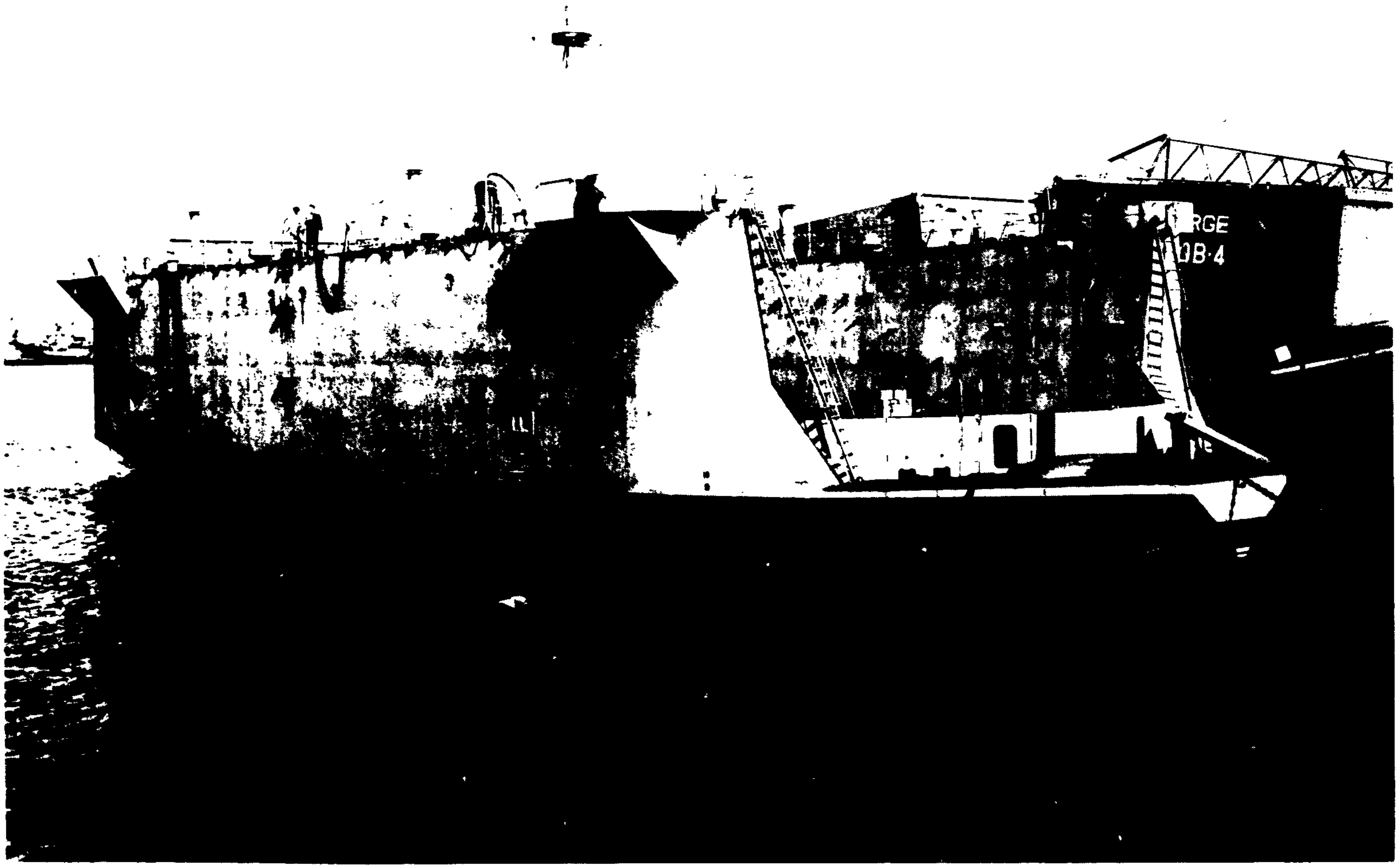


Figure 1. AFDL-12 Floating Drydock.

INTRODUCTION

The Bureau of Yards and Docks maintains, in an inactive status, a large number of floating drydocks for use in national emergencies. Preservation techniques should satisfy two basic requirements: (1) They should result in longer life for the structure, and (2) they should accomplish this at minimum cost.

The use of protective coatings and dehumidification has proven effective in preserving the interiors of inactive drydocks, but exterior preservation is not obtained so easily. The application and reconditioning of paints above the waterline is readily accomplished, but continuously submerged surfaces can be recoated only while the structure is completely out of the water; consequently, the area below the waterline is of major concern.

Damage to the paint system below the waterline comes from several sources:

1. Floating and submerged debris may strike or rub against the hull, causing the loss of paint.

2. Minute perforations in the paint film may exist to serve as focal points for accelerated corrosion and loss of paint through undercutting.

3. The planned breakdown of antifouling paint will eventually expose, to attack by marine life, other layers of an underwater paint system.

4. Additional paint may be removed by the separation from the hull of accumulations of marine fouling.

Hull deterioration which results from failure of the paint film might be minimized or even eliminated by application of some type of cathodic protection.

The basic principle of cathodic protection has been used since 1824, when Sir Humphrey Davy recommended attaching cast iron or zinc plates to the copper hulls of Admiralty vessels. The use of cathodic protection is no longer limited to ships; systems are commonly installed for protecting water tanks and mains, oil pipe lines, and other buried public utilities. Chemical producers and oil refiners frequently use some method of cathodic protection in extending the service life of their installations. Increasing attention is being given to the cathodic protection of structures immersed or submerged in sea and brackish water, and builders and operators of ships are using it to protect both interior and exterior hull surfaces.

The U. S. Naval Civil Engineering Laboratory conducted studies of several systems for applying cathodic protection to floating structures. Beginning with an impressed current system on a single AFDL-class drydock, the studies progressed through investigations of galvanic (sacrificial) anode systems for single hulls to impressed current systems for multiple hull installations. Allied studies included the compatibility of paints with cathodic protection and of floating corrosion inhibitors with cathodic protection, the cathodic protection of the interiors and exteriors of active floating structures, and automatic control systems for cathodic protection installations.

For some time prior to March 1950 the Bureau had been investigating the possibility of using cathodic protection on the exterior underwater hulls of floating drydocks. The Bureau and the National Carbon Division (NCD) of the Union Carbide and Carbon Corporation agreed to make an experimental installation on an inactive floating drydock. NCD would furnish anodes and leads and would assist in making preliminary and subsequent investigations as well as in supervising the installation of the system. The Bureau would provide all additional equipment, materials, and labor. The Laboratory was instructed to provide all services for the Bureau, to make inspections and submit reports, and to make the necessary arrangements with the NCD representative and the Public Works Officer at Long Beach.

INACTIVE DRYDOCK STUDIES

AFDL-12 Installation Details

The AFDL-12, shown in Figure 1, was selected as the test vessel. It is a 1000-ton drydock, with an underwater surface of approximately 12,000 square feet, moored in the inner harbor at the Long Beach Naval Station. The cathodic protection system consisted of a rectifier, a single anode, and the necessary connecting cables. The Signal Corps RA-91A rectifier was housed in a sentry-type building. A positive lead, made from No. 4 AWG single-conductor submarine cable, was connected by a waterproof splice to the 4-inch-diameter by 40-inch-long sodium-treated graphite anode. The anode was placed under the bow of the AFDL-12 in about 28 feet of water. A negative lead was installed between the hull and the rectifier. Because steel is best protected when maintained at a polarity of 850 mv relative to a copper-copper sulfate half-cell, it was intended to maintain the AFDL-12 near that value.

After four days of operation, a second anode was connected to the positive lead and placed under the AFDL-12 stern for three months. The two anodes were then replaced by a single anode under the center of the drydock. After one month the single anode was replaced by a "remote" anode 400 feet from the hull in shallow water. Six weeks later, the remote anode was disconnected and replaced by the single centrally located anode. Data obtained indicated that a single anode lying on the bottom and with an output of somewhat less than 8 amperes (2 amperes per square foot of anode surface) protected the hull adequately.[1]

A bench-scale evaluation of the paint-stripping effects of cathodic protection was conducted in order to decrease the inspection time at Long Beach. The same types of paints used on the AFDL-12 were applied to mild-steel plates which were then placed in a sea water bath. The tests were conducted under two conditions: (1) fixed current and, (2) fixed polarization regardless of current requirement. It was determined that with polarization maintained near the optimum value of 850 mv no damage of importance was done to either the Formula 14 anti-corrosive primer or the Formula 15 hot-plastic antifouling paint. With fixed current (between 15 and 20 milliamperes per square foot) the Formula 15 hot plastic was completely removed.[2] A current density in excess of 0.5 ma per square foot on recently painted steel results in over-polarization of the steel and blistering of the paint.

Initially, the polarization and current distribution was established by a survey made around the perimeter of the ship. To obtain similar information about the large underwater-hull areas, a "keel-haul" ring was fabricated. This device, shown in Figures 2a and 2b, was used to carry a reference half-cell to many locations on the bottom of the hull, making it possible to plot equi-potential lines for the underwater surface.

The single anode system, using current from the RA-91A rectifier, operated continuously for 18 months. Two changes were noted during the latter part of the period: (1) to maintain adequate polarization it was necessary to increase the current from 7.6 amperes to 12 amperes, and (2) a white mineral was deposited on the hull from waterline down. Analysis showed a calcium to magnesium ratio of 38. It was further noted that marine growth was quite heavy; this was attributed to the more stable condition of a non-corroding surface.[3]

At the end of the period, two Yard Repair vessels were moored alongside; (about four years later, a third YR was included in the common system). Three more anodes were added, and increased current was provided by three more RA-91A rectifiers. Polarization data three weeks later, shown in Figure 3, indicated that the two newer vessels had considerable exposed metal below the waterline. An additional anode was connected to each of the three anodes installed to accommodate the YR's, and another pair of RA-91A rectifiers was added. The single anode under the AFDL

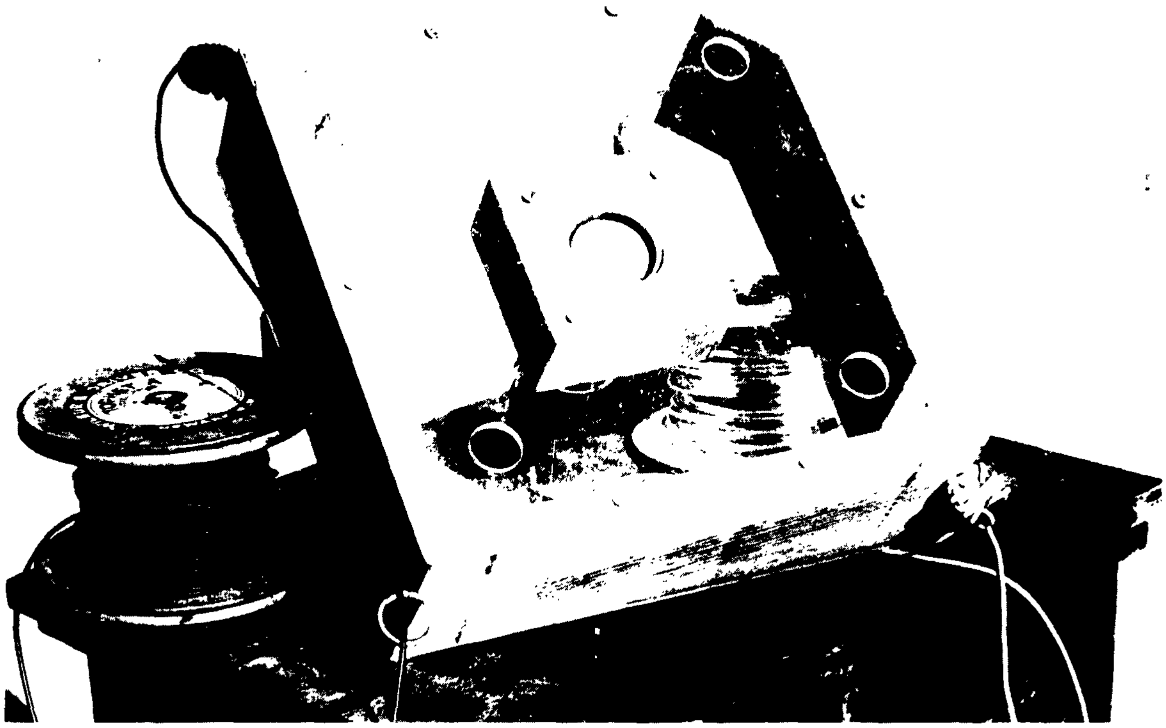


Figure 2a. Bottom, keel-haul rig.

Figure 2b. Top, keel-haul rig.

had been moved to the other side at the time the two YR's were moored alongside, and it was connected to the AFDB rectifier (described later). Current supplied by the auxiliary rectifiers, plus that supplied to the single anode from the AFDB system, was not sufficient to provide full protection.

AFDL-12 Tests

As part of the early AFDL-12 installation, four pre-weighted clean steel coupons, 1-foot square by 3/16-inch thick, were placed at the bow and stern in 2-1/2 feet of water. Of the two coupons in each location, one was bonded to the hull with a length of submarine cable and the other insulated from the system. When the unprotected coupon was removed 3 months later, it had lost 48.5 grams, equivalent to an average rate of 5.2 mils per year (mpy); the protected coupon lost 0.5 gram, or about 0.054 mpy. The apparent reduction in corrosion rate for the protected coupon was 99 percent. After the measurements were completed the panels were coated with Formula 14 anticorrosive paint and installed as before.[1]

Nine months after the bow pair was removed, the stern pair was examined. The unprotected coupon had been losing metal at the rate of 6.6 mpy, while the protected coupon was losing only 0.89 mpy. The reduction in corrosion rate was 86.5 percent. The bow pair was examined periodically, and no peeling or stripping of paint from the protected coupon was observed. Rusted areas on the unprotected coupon showed complete loss of paint from those areas.[2]

AFDB-4

Further expansion of the program was provided through installation of a graphite anode system on the AFDB-4, shown in Figure 4. This seven-section drydock, moored in Long Beach Harbor, was included to demonstrate the possibility of integrating several hulls into one cathodic protection system.

To provide the necessary current distribution for the AFDB-4, three cable networks were considered:

1. The most nearly ideal arrangement would consist of a positive and a negative buss running along the shore opposite the drydock sections. All leads between the anodes and the positive buss would be the same length, and this would be true of the leads between the individual sections and the negative buss, as shown in Figure 5a.

2. The second network to be considered provided for electrical paths of equal physical length through the several anodes, as shown in Figure 5b. The main connecting cable would have to be very large in order to minimize power losses.

3. The third network (the one actually used) consisted of a network of smaller cables in which no one cable carried all of the current, as shown in Figure 5c. Rheostats in the shorter anode leads were adjusted to equalize the voltage drops or to satisfy the need for differential anode currents.

Protection began in March 1952, with the system consisting of five anodes and two negative returns, as shown in Figure 6a; when more cable and anodes became available, the system was revised, as shown in Figure 6b. By November 1952, the system consisted of nine anodes and separate negative returns from each hull to the rectifier. The network as used resulted in an uneven current distribution, so an additional lead was run out to the far end, and resistances were added to the leads to the nearest anodes.

Initially all sections were bonded together with fourteen-foot lengths of No. 4 AWG cable, but the resistance of the cable was about equal to that of the sea water path between the hulls. Hence, there was no assurance that current tending to flow between sections would go through the cable rather than the sea water. Larger bonding cables were installed at a later date to eliminate interaction between the hulls.

Power for the system was supplied by a special rectifier. The rectifier was a convection-cooled, dry-disc, selenium type, with an input of 208 vac, 60 cycle, 3 phase. By means of a Variac in the input side, the output could be varied between 0 and 15 vdc, and up to 300 amperes. Auxiliary rectifiers (three RA-91's and one RA-91A) were available for emergency use or expansion of the installation.

Anodes made of specially treated graphite were supplied by the National Carbon Company. Each anode was four inches in diameter and 40 inches long and was supplied with a length of cable for connecting to the lead from the power supply.

For the year October 1952 to October 1953 the AFDB system was found to give adequate protection and remained unchanged. Documentation of the effectiveness of this system was provided by test coupons of mild steel. Each coupon was connected to a length of electric cable with a waterproof joint and suspended in the water. Half of the cables at each location were bonded electrically to the hull; the other half were attached so that the coupons were insulated from the hull.

Table I shows that corrosion of coupons on the multiple hull system was reduced to a negligible degree.

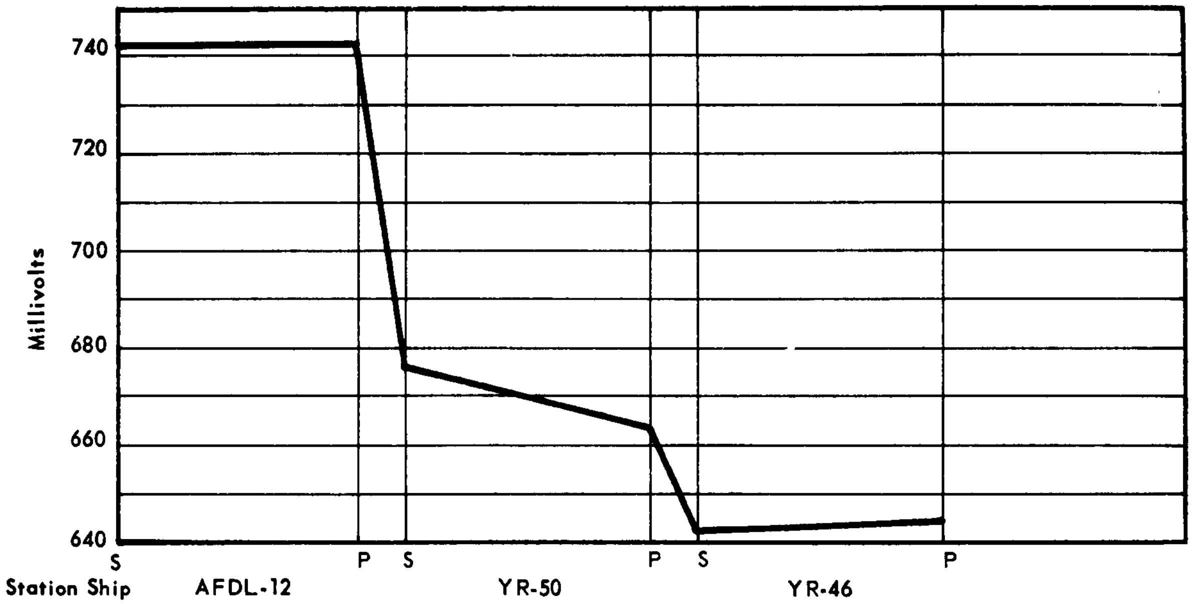


Figure 3. Hull polarization 3 weeks after installation of cathodic protection.

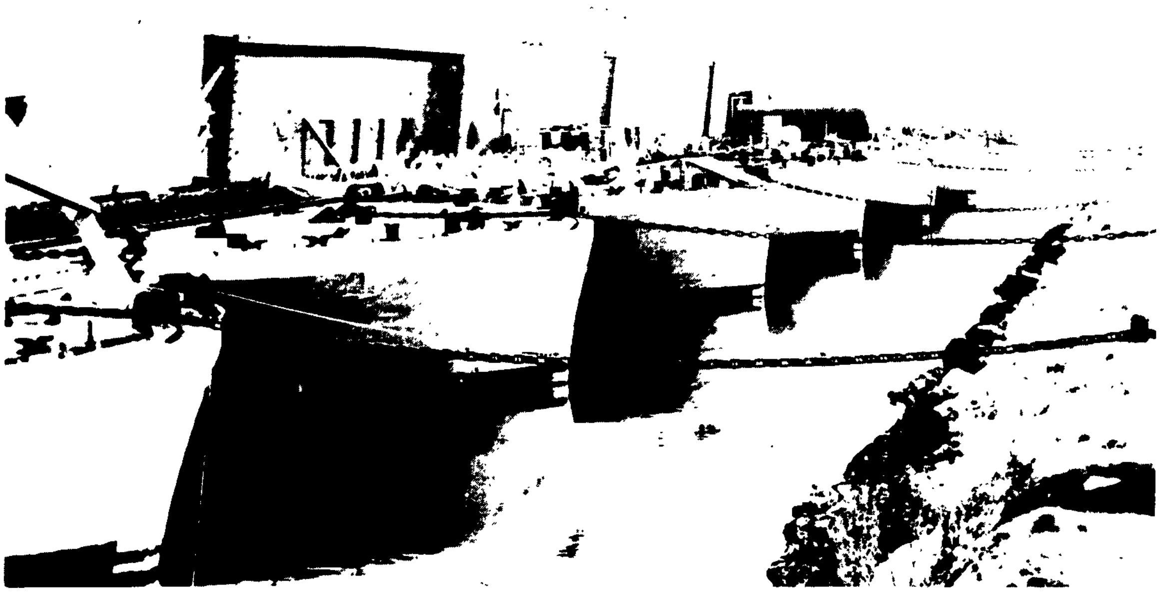


Figure 4. AFDB-4 Floating Drydock.

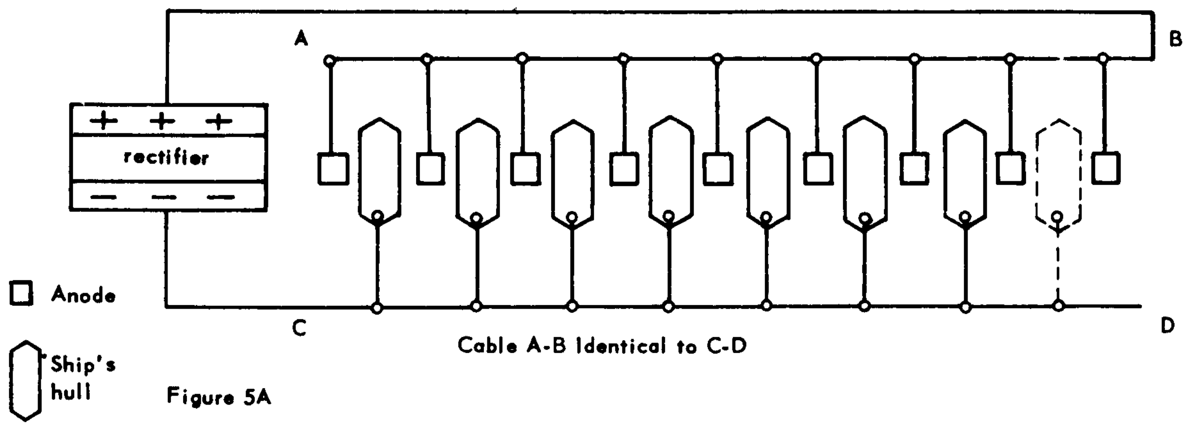


Figure 5A

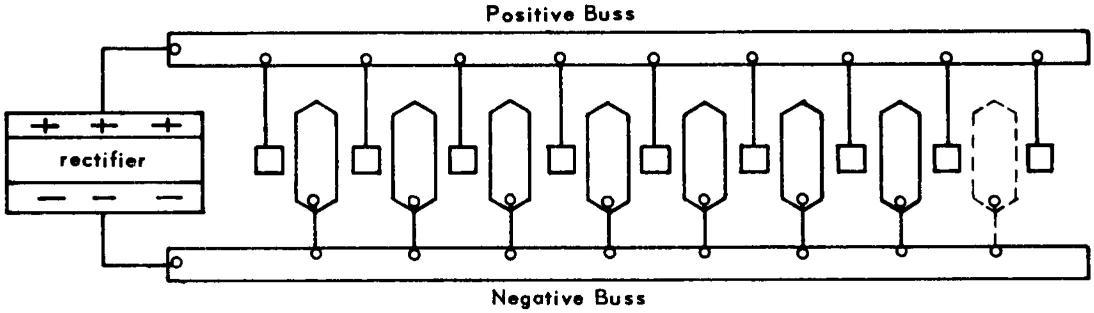


Figure 5B

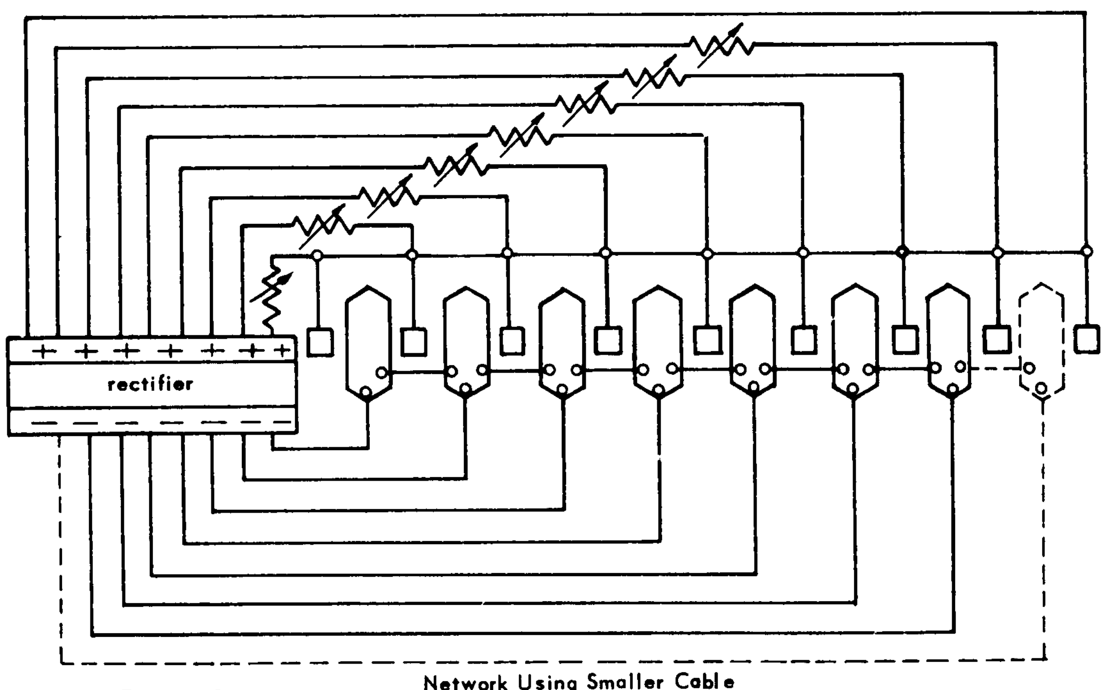
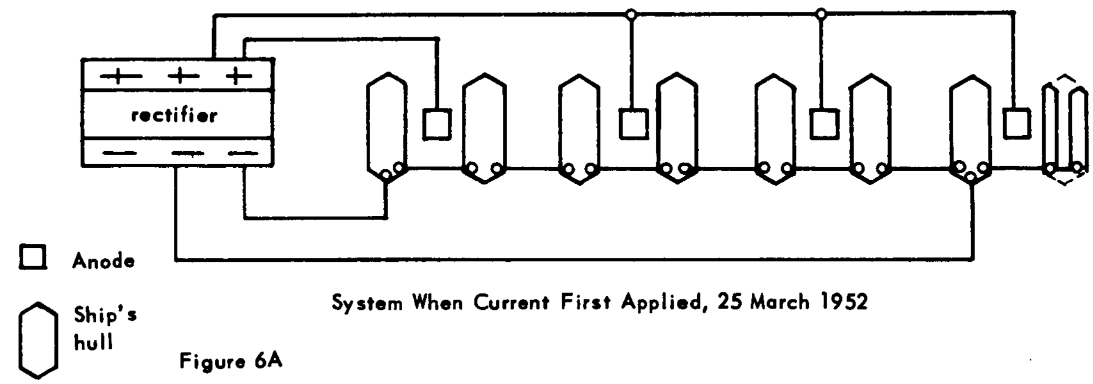


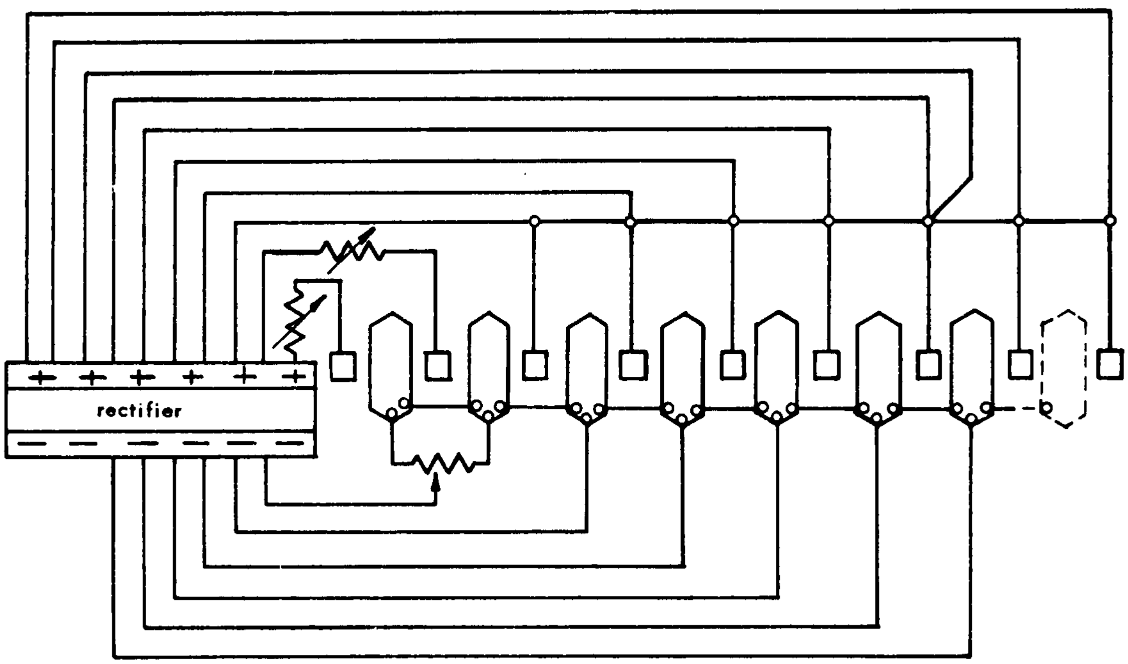
Figure 5C

Figure 5. Three cable arrangements for sectional drydock.



System When Current First Applied, 25 March 1952

Figure 6A



System as of 3 November 1952

Figure 6B

Figure 6. Cable arrangements used at Long Beach.

Table I. Reduction of Corrosion Through Cathodic Protection

Coupon Number	Coupon Location	Type of Anode	Total Weight Loss (gm)	Corrosion Rate (mils per year)	Corrosion Rate Reduction (percent)
1 3	AFDL-20 Port Hueneme	Magnesium None *	9.5 121.0	0.40 5.1	92
2 4	AFDL-20 Port Hueneme	Magnesium None *	29.0 129.9	1.2 5.5	78
10 6	AFDB-4 Section Baker Long Beach	Graphite None *	5.7 144.0	0.28 7.1	96
7 12	AFDB-4 Section Charlie Long Beach	Graphite None *	0.0 115.5	0.0 5.7	100
13 14	AFDB-4 Section Easy Long Beach	Graphite None *	0.8 141.2	0.042 7.3	99
23	AFDB-4 Section Fox Long Beach	Graphite	0.0	0.0	100

* Insulated from hull.

Beginning with March 1953, individual AFDB sections were removed for reconditioning and then returned to the mooring point. Abnormal aging of the rectifier stacks resulted in a lack of reserve power; this, coupled with the removal and addition of hulls caused appreciable instability in the system.

During the period that the sections were in drydock, hydrostone molds were made of six to eight areas on each hull. Both color and black and white photographs were taken of the same areas, and the locations were recorded. Photographs of one area and the corresponding hydrostone mold are shown in Figures 7a and 7b. Eight pre-weighed steel coupons were welded to each hull between the skegs below the waterline; on one section, four of the eight coupons were mounted on a bakelite strip to simulate unprotected metal. Additional boxes or portable plates 20 inches square and extending 2 inches from the hull were welded amidships 4 feet below the waterline. The boxes were filled with a preservative and the assembly simulated the actual hull. It was planned that the photographs and molds would be duplicated and the coupons removed when the sections were next drydocked.[4]

During the early stages the method of controlling current was to disconnect anodes. Such a method was satisfactory up to a point, but more than once produced an abnormal reduction of polarization. To eliminate future recurrences of the problem, a power rheostat was installed in the ground return line from each section. This addition made finer and more individual current adjustments possible, and thus permitted compensation for uneven changes in the condition of the underwater paint systems. Shunts, a tap switch, and an ammeter were installed in addition to the rheostats to provide a means for measuring the current from each section.

AFDB-4 and AFDL-12 Combined Systems

In February 1954, the two systems at Long Beach were combined and operated as a single system, as shown in Figure 8. One rectifier delivered all the power to the anodes through a common buss. Figures 9a and 9b show a control panel which provided for individual measurement and control of the return currents from each separate hull. Variations in current and polarization records up to November 1954 were attributable to several sources: replacement and test of new selenium stacks in the rectifier, extensive movement of the AFDB-4 sections, and installation and experimentation with an electronic servo current control system shown in Figure 10.

Figure 7a. Hull surface.

Figure 7b Reversed photograph of mold of same surface.

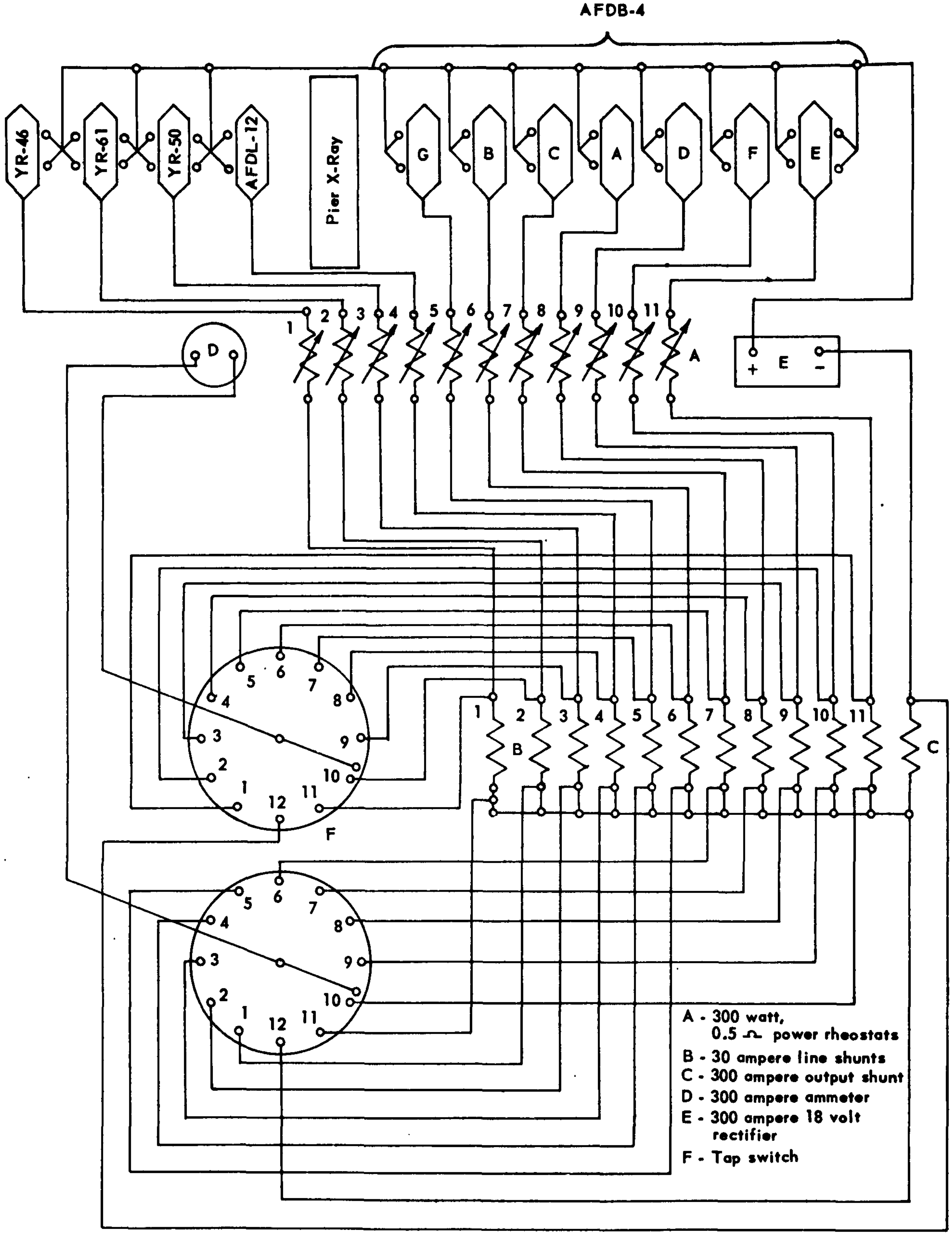


Figure 8. Cathodic protection system for combined installation at Long Beach.

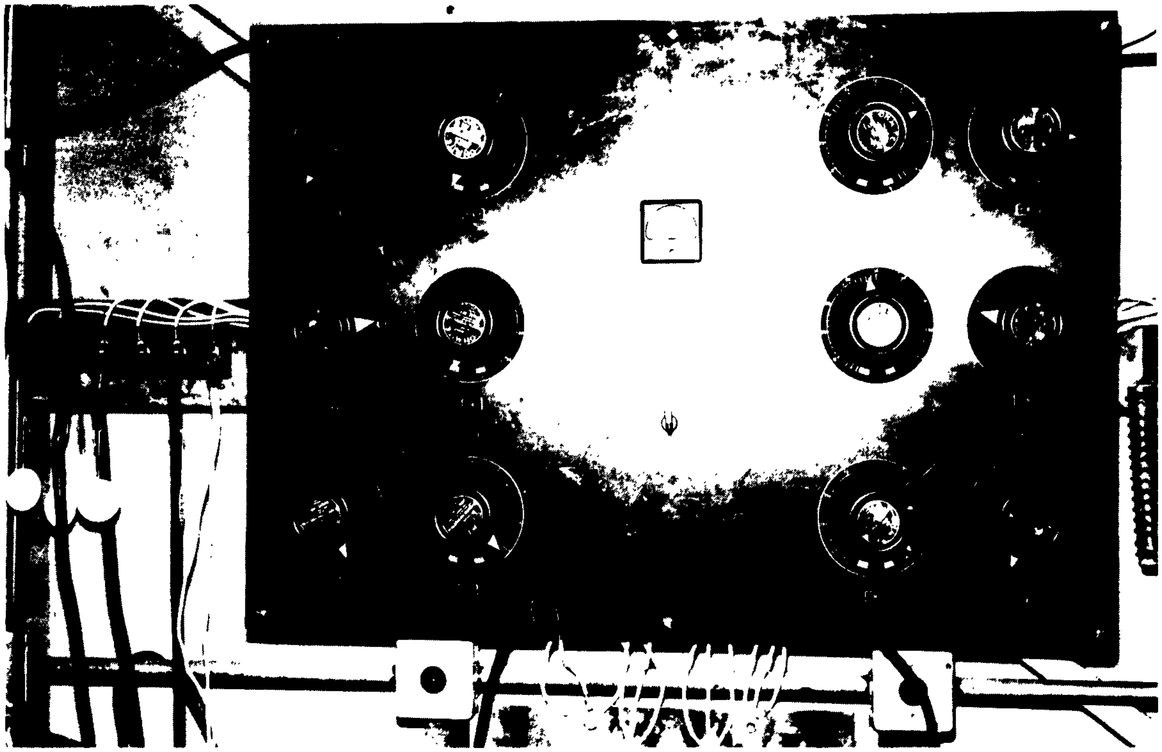


Figure 9a. Front of control panel for Long Beach cathodic protection system.

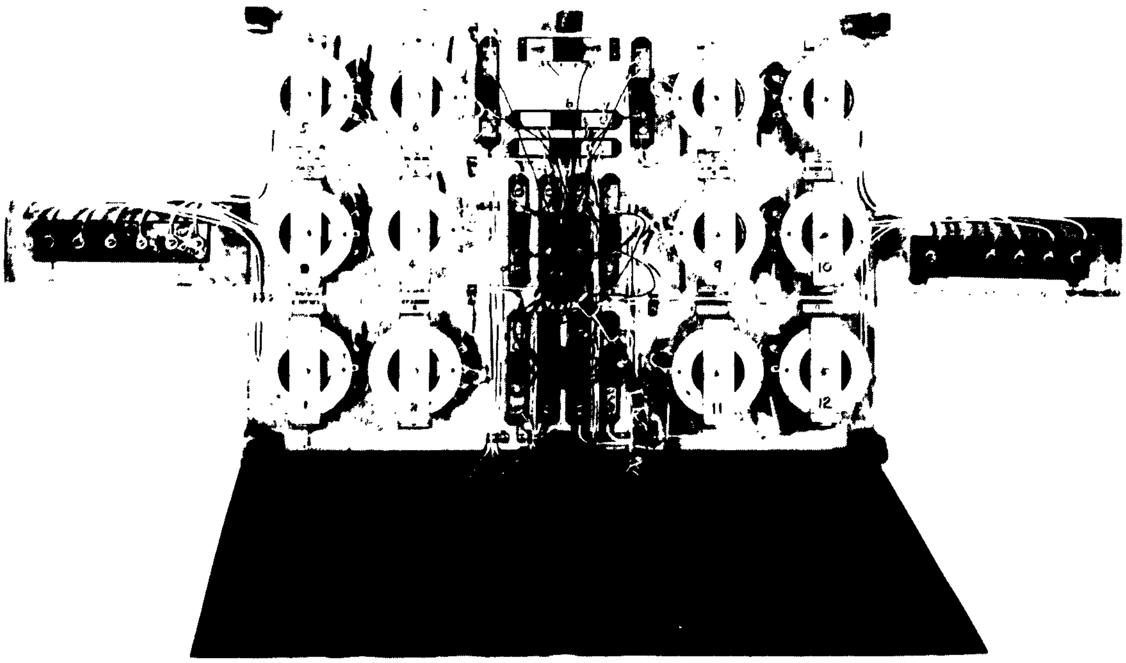


Figure 9b. Rear of control panel for Long Beach cathodic protection system.

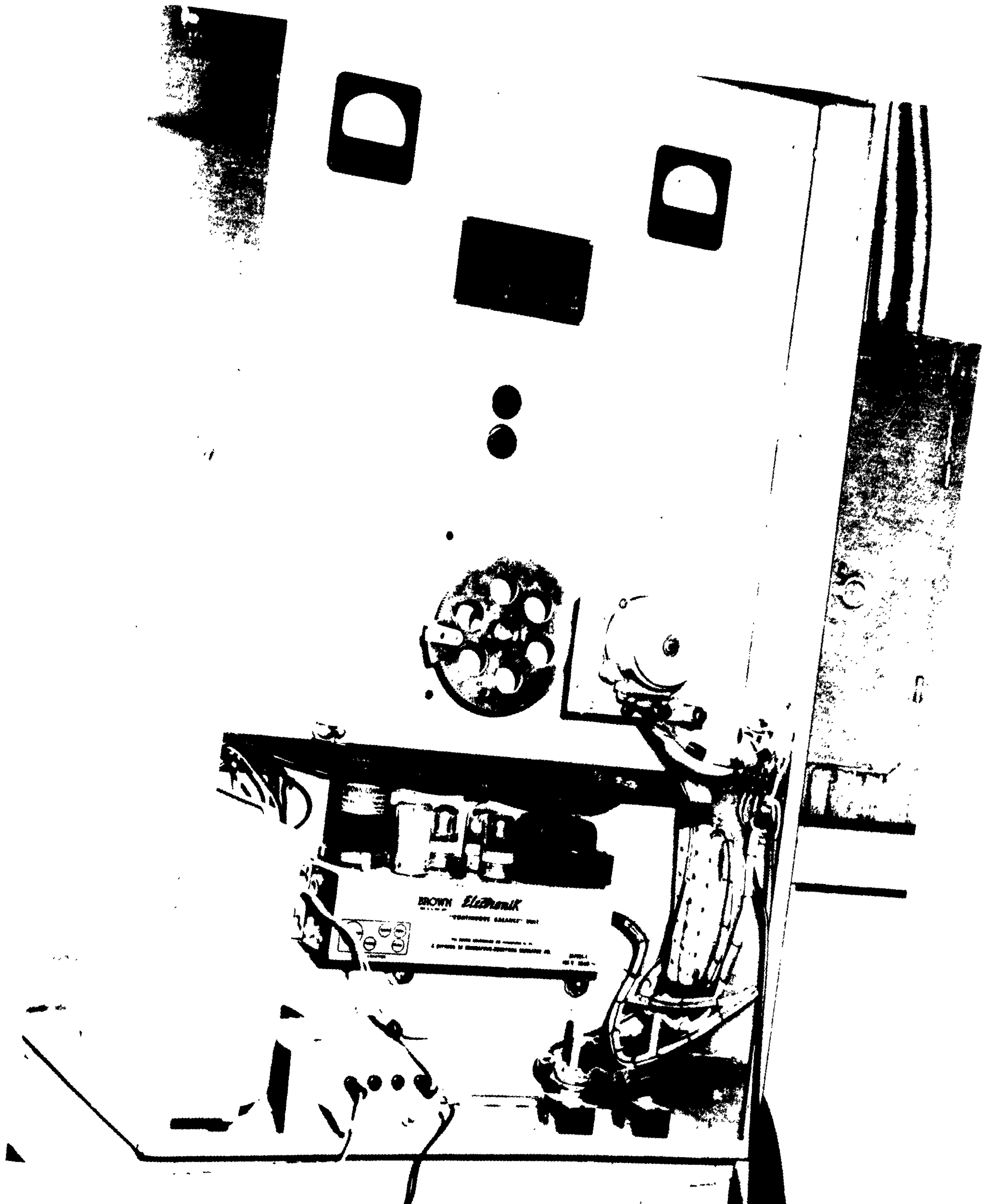


Figure 10. Automatic current control unit.

As the AFDB sections were returned to the system following their quinquennial reconditioning, the current requirements for individual hulls decreased from a maximum of 30 amperes before to about 3 amperes after reconditioning. Hull polarization up to November 1954 was maintained between 750 and 900 millivolts, rather than at the value of 850 millivolts recommended for painted structures. Factors contributing to the fluctuation could generally be classified into groups: (1) weekly inspections of the facility were scheduled, but that would not permit prompt repairs to anode leads and ground return lines when broken. Also, the sections were moved without notice to project personnel. (2) Experimentation with control methods and anode location has certain inherent limitations which promoted abnormal fluctuations in polarity.

When first placed under cathodic protection in 1950 the AFDL-12 required eight amperes for proper protection; about four years later the requirement was ten amperes. Experience with the AFDB-4 indicated that if the AFDL had been placed under cathodic protection immediately after reconditioning in 1948, it would have required only 1.5 amperes because of paint imperfections.

Bare steel can be protected adequately by applying 5 ma per square foot. It was calculated that in the two years between reconditioning and installation of cathodic protection, the exposed area on the AFDL increased by 1300 square feet, or about 650 square feet per year. In the four-year period following the cathodic protection installation the 2-amperes current increase indicated the exposure of an additional 400 square feet, or about 100 square feet per year. Thus, after application of cathodic protection, the rate of bare metal exposure was decreased to one-sixth of the previous rate. Since the antifouling paint had an estimated life of two years, part of the high rate of steel exposure may be attributable to the expected breakdown of the paint.

Operation of the Long Beach system revealed many factors which require consideration when systems are designed to protect several hulls. For example, the decision as to whether anodes should be suspended from the hulls or placed on the bottom may depend on frequency of hull movements in and out of the site, silting conditions, and the possibility of damage to cables leading to or lying on the shore. The shore embankment consists of large, sharp-edged rocks; these occasionally roll down and may have ruptured the cable insulation in more than one instance. Silt deposited on anodes reduces the effective area and causes more rapid deterioration of the anode. This possibility can be somewhat minimized by keeping the anode off the bottom. One method is displayed in Figure 11 which shows a 4-inch-diameter by 80-inch-long graphite anode mounted in a bakelite support. The large area on the bottom of the support would keep the anode from settling into the silt. In the view shown, the anode and support have been in use for eight months, and both are in excellent condition.[4]

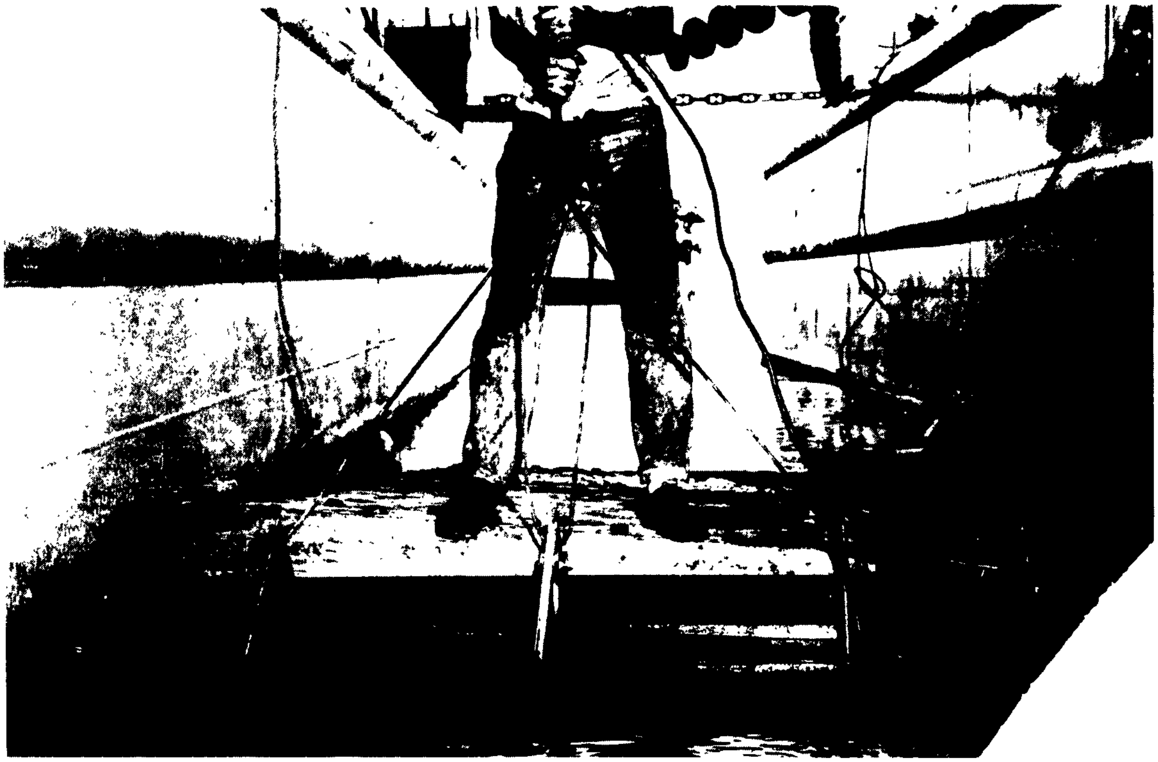


Figure 11. Bakelite support for 4-inch by 80-inch graphite anode.

Use of suspended anodes can result in appreciable strain on the anode cable. Small anodes may be suspended without difficulty, but when it is advisable to use larger anodes (as 4-inch-diameter by 80-inch-long), strain on the lead wire must be minimized. A method for accomplishing this is detailed in BuDocks Instruction 11012.55.[5]

In another method two holes were drilled through a 4-inch by 80-inch anode. Plastic pipe was fed through the holes, and Monel wire through the pipe to form a loop. The loop was fastened to a stainless steel wire swing hanging between two drydock sections. To insure that no strain would be placed on the anode lead connection, the lead wire was loosely taped to the support wires. In three years, this anode became very soft and porous, and suffered considerable end deterioration.

Periodic examination of anodes revealed an unusual amount of deterioration of the neoprene seal and insulation at the connection between the anode and lead wire. This was somewhat alleviated by supplementing the neoprene washer with one of graphite and by coating that end of the anode with an epoxy resin. Additional attempts to halt deterioration of the neoprene included the application of rubber and plastic insulating tape, and the fitting of unplasticized polyvinyl chloride adapters to the ends of the anodes. The adapters were then filled with an insulating material.

Different sizes of graphite anodes were installed, and a number of Duriron anodes were used also. One of the latter was examined three months after placing, and in addition to a cover of a soft grey material, one-eighth-inch-deep pits were observed. Subsequent electrical measurements revealed that the current being discharged by the Duriron anodes was too low, so they were removed. Project personnel felt that the differences in electrical characteristics rendered graphite and Duriron incompatible in this installation.

Among the graphite anodes tried were some 12 inches in diameter and 12 inches in length. Pairs of these, after being connected to the system, were placed on the bottom with and without support underneath and suspended by the lead wire. Two years later all were in about the same condition, with only the neoprene at the lead connections being damaged. A number of Hypalon washers were cemented over the affected areas to protect the buna rubber insulation.

The different graphite anodes generally had a fairly long life, as long as the rated amount of current was not exceeded. Current in excess of one ampere per square foot of anode surface was not recommended for graphite. For a number of 4-inch-diameter by 40-inch-long anodes in the AFDB group, the estimated life was 3 to 5 years when discharging currents of 5 to 10 amperes each, or about 1.4 to 2.8 amperes per square foot.[4]

Some softening of the surface occurred, and the rounding of sharp corners was commonplace. The major causes of abnormal graphite deterioration were excess current, and partial or complete coverage by silt from contact with the harbor bottom. The cures for such conditions are to provide additional anodes before the rated current capacity is exceeded and to keep the anodes up from the bottom.

It is felt that the AFDB-4 and the other hulls have been adequately protected. Examination of the current and polarization records (Figures 12a through 12g) will show that periods of overprotection (polarization greater than 1,000 mv) have amounted to only 7 percent of the total period. If the generally accepted degree of polarization of 800 millivolts is taken as the minimum, the hulls have been underprotected for 23 percent of the time; on the other hand, 750 mv might be taken as the minimum. This was true for many months, and the periods of underprotection amount to just a little more than 6 percent of the total. The amount of actual damage can be determined only by direct examination.

Perhaps the most important observation was the great variation between weekly polarity values. This variation did not occur to any extent during 1955 or the first months of 1956 while the system was under control by electronic and magnetic servo systems. From 15 January to 20 May 1957, the same was true; during this period the system was being controlled by a magnetic amplifier unit. It is thus indicated that when a steel surface in sea water is under cathodic protection, the polarization of the steel can be held within acceptable limits by automatic control devices.

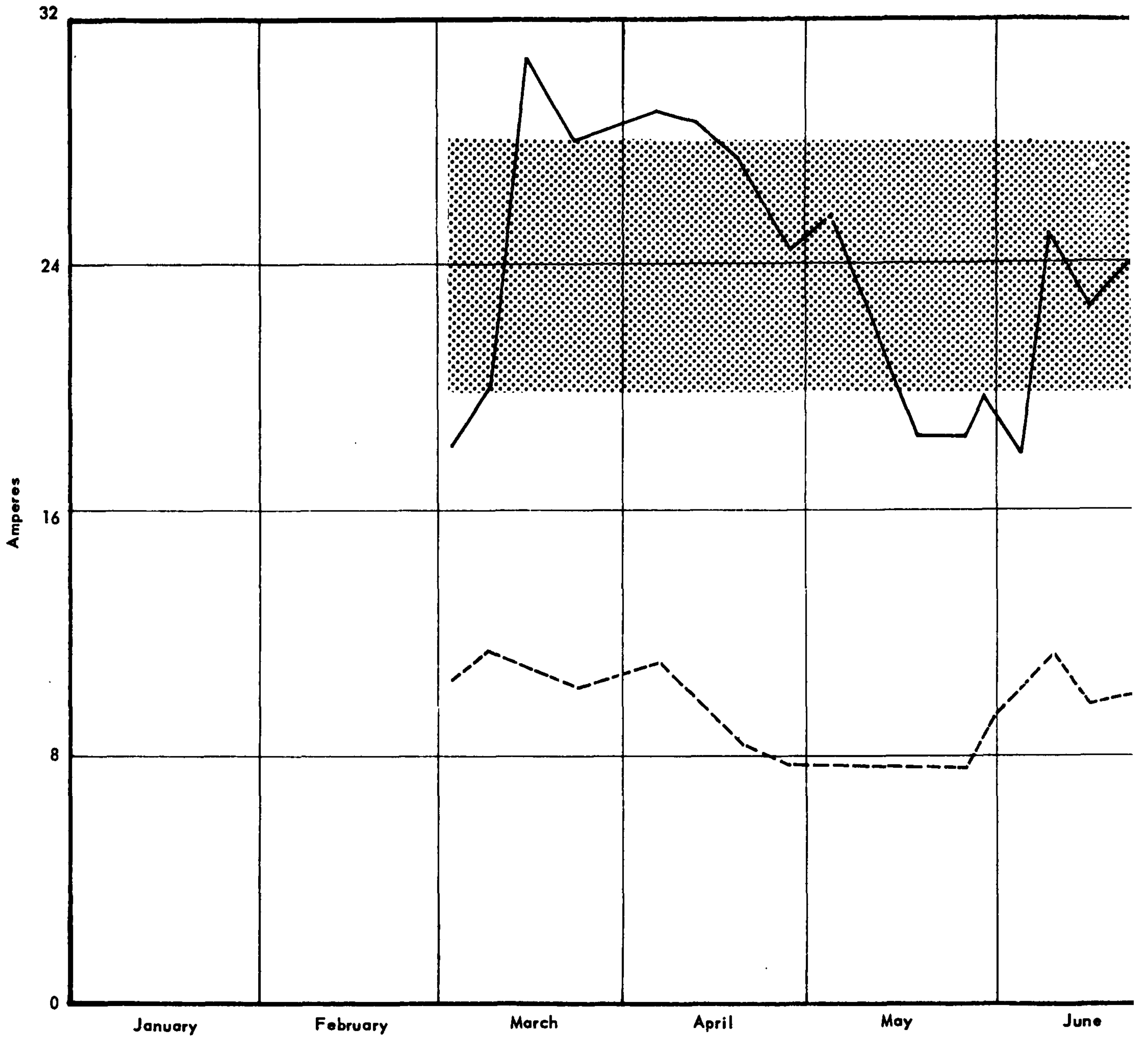
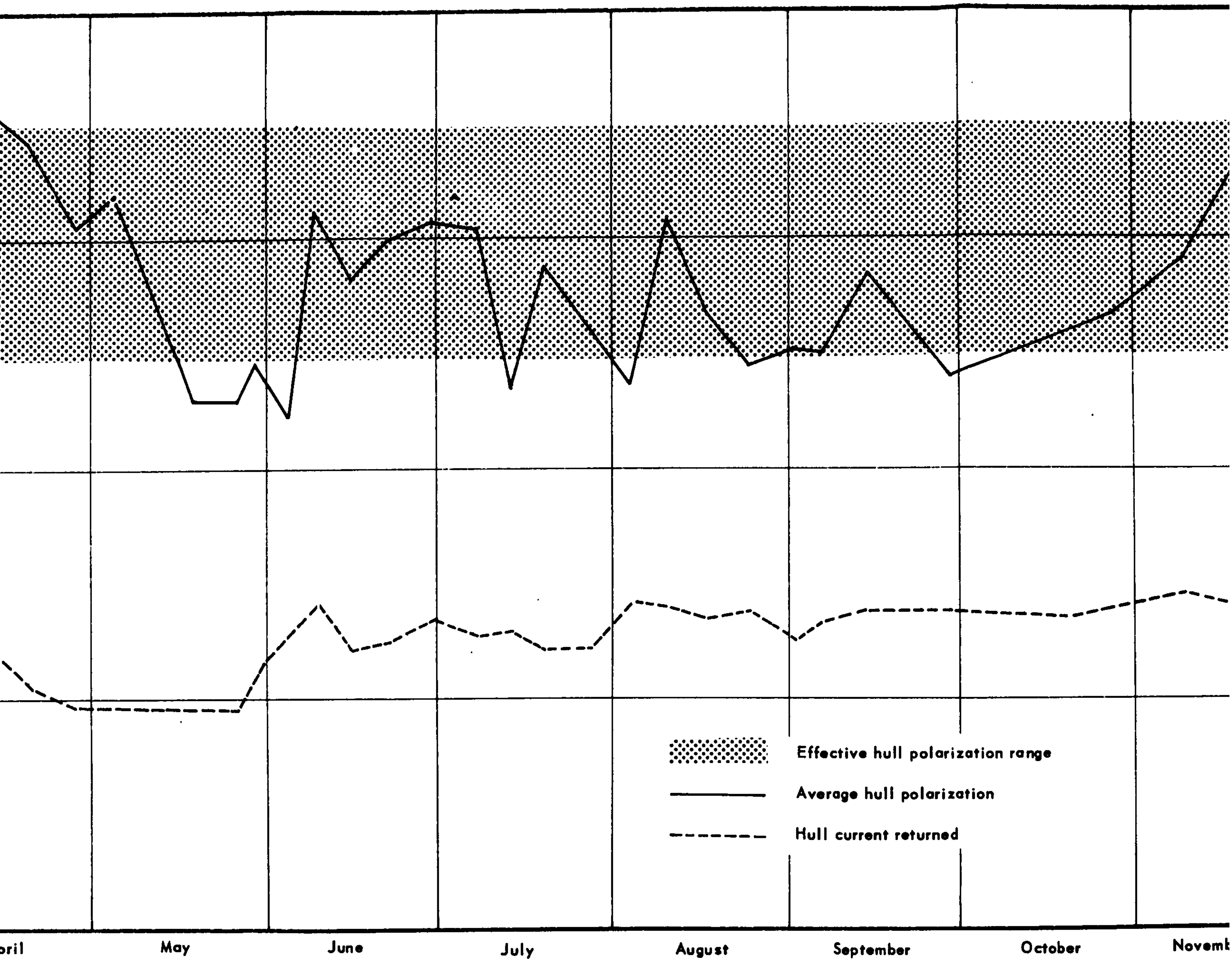


Figure 12a. Current and polarization re



12a. Current and polarization records for 1954 for typical AFDB-4 section.

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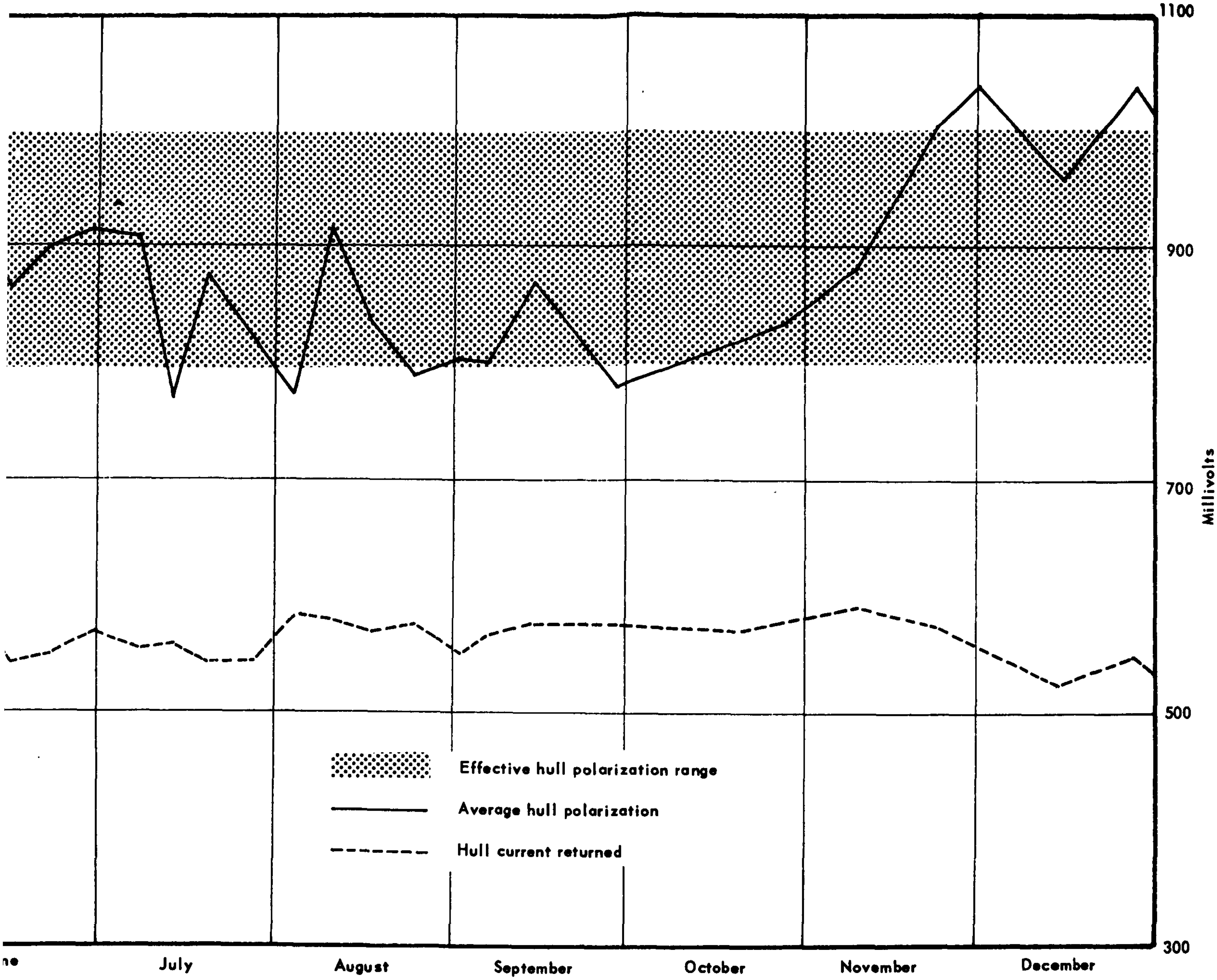

n records for 1954 for typical AFDB-4 section.

3

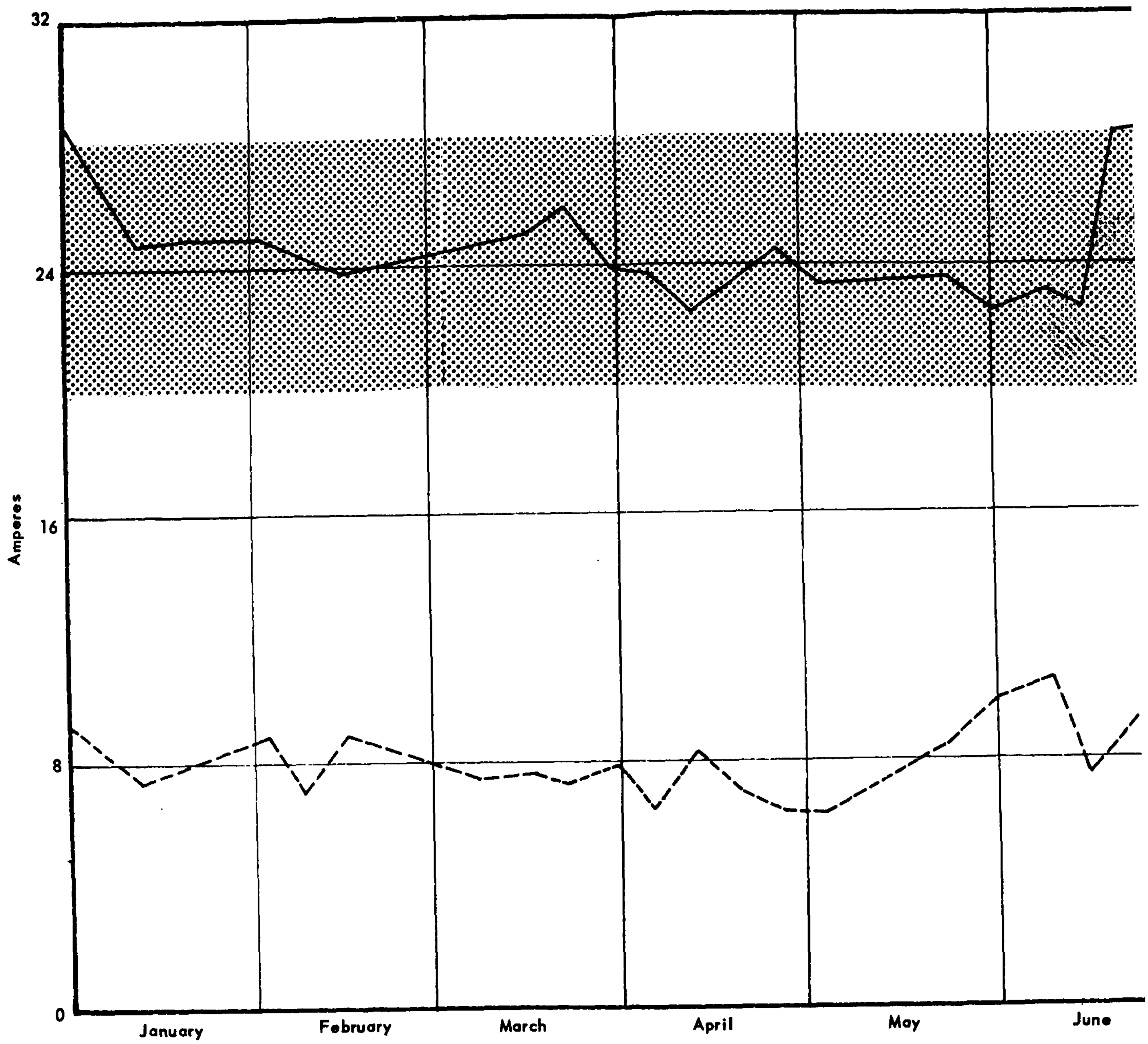

Figure 12b. Current and polarization r

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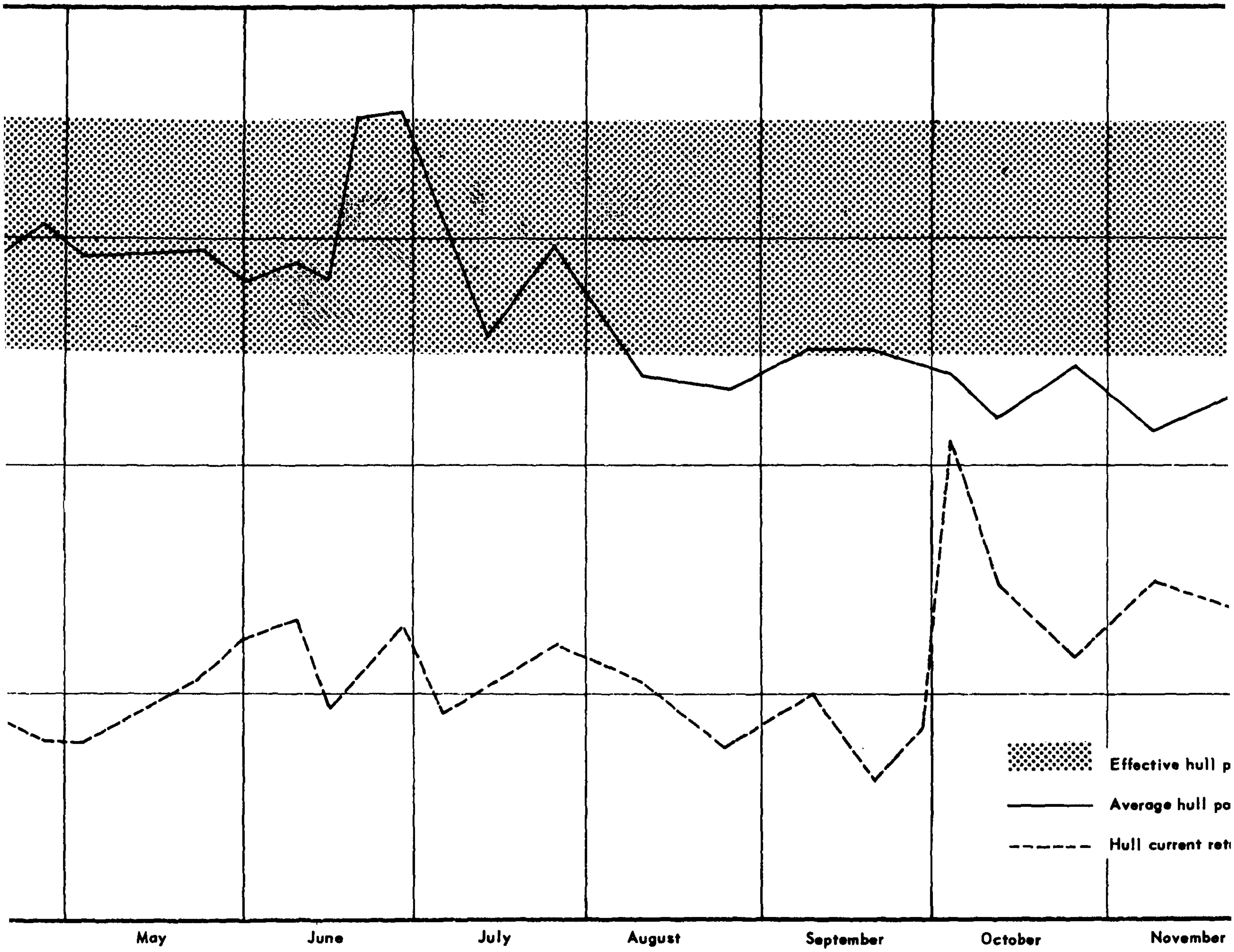
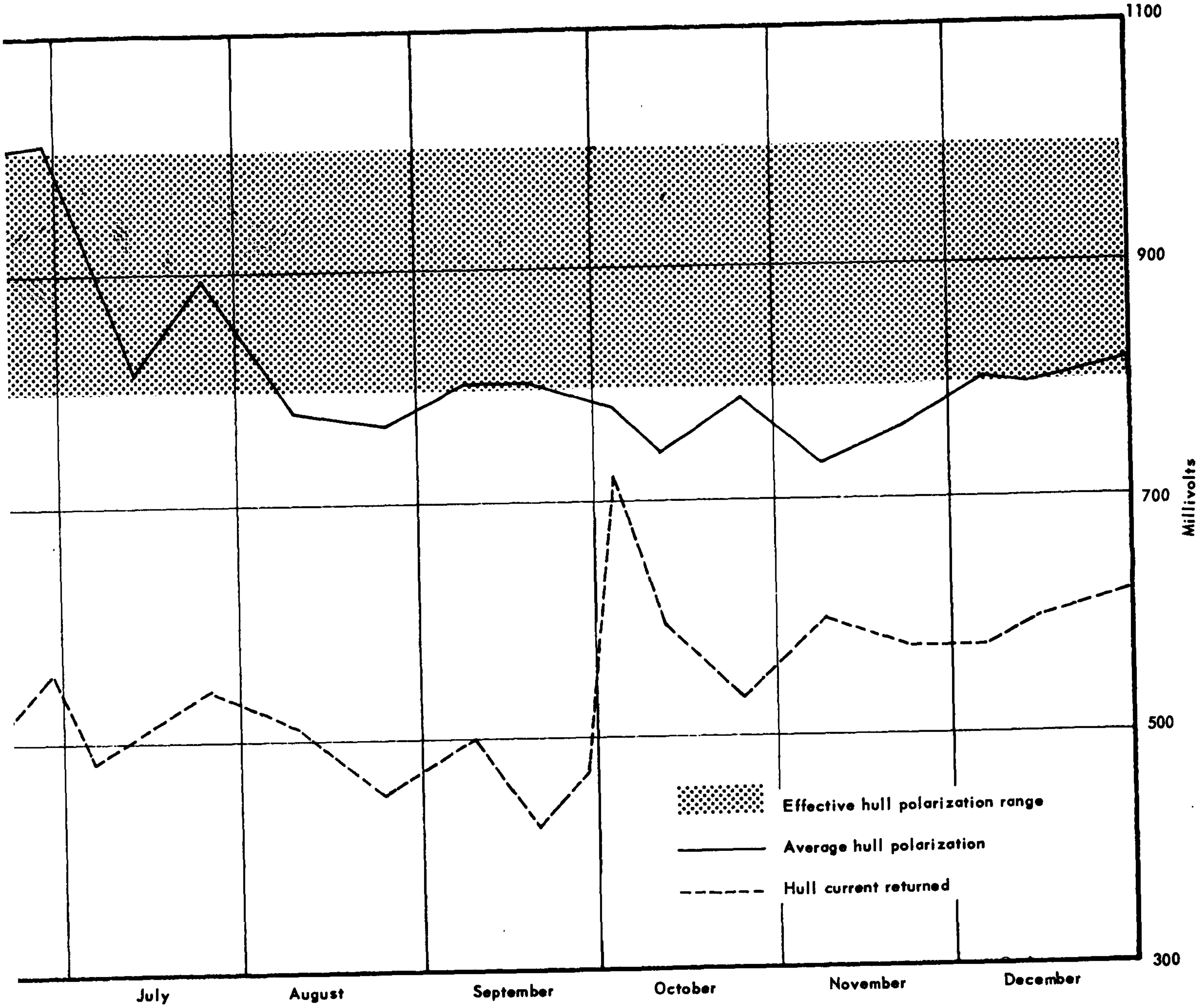


2b. Current and polarization records for 1955 for typical AFDB-4 section.



records for 1955 for typical AFDB-4 section.

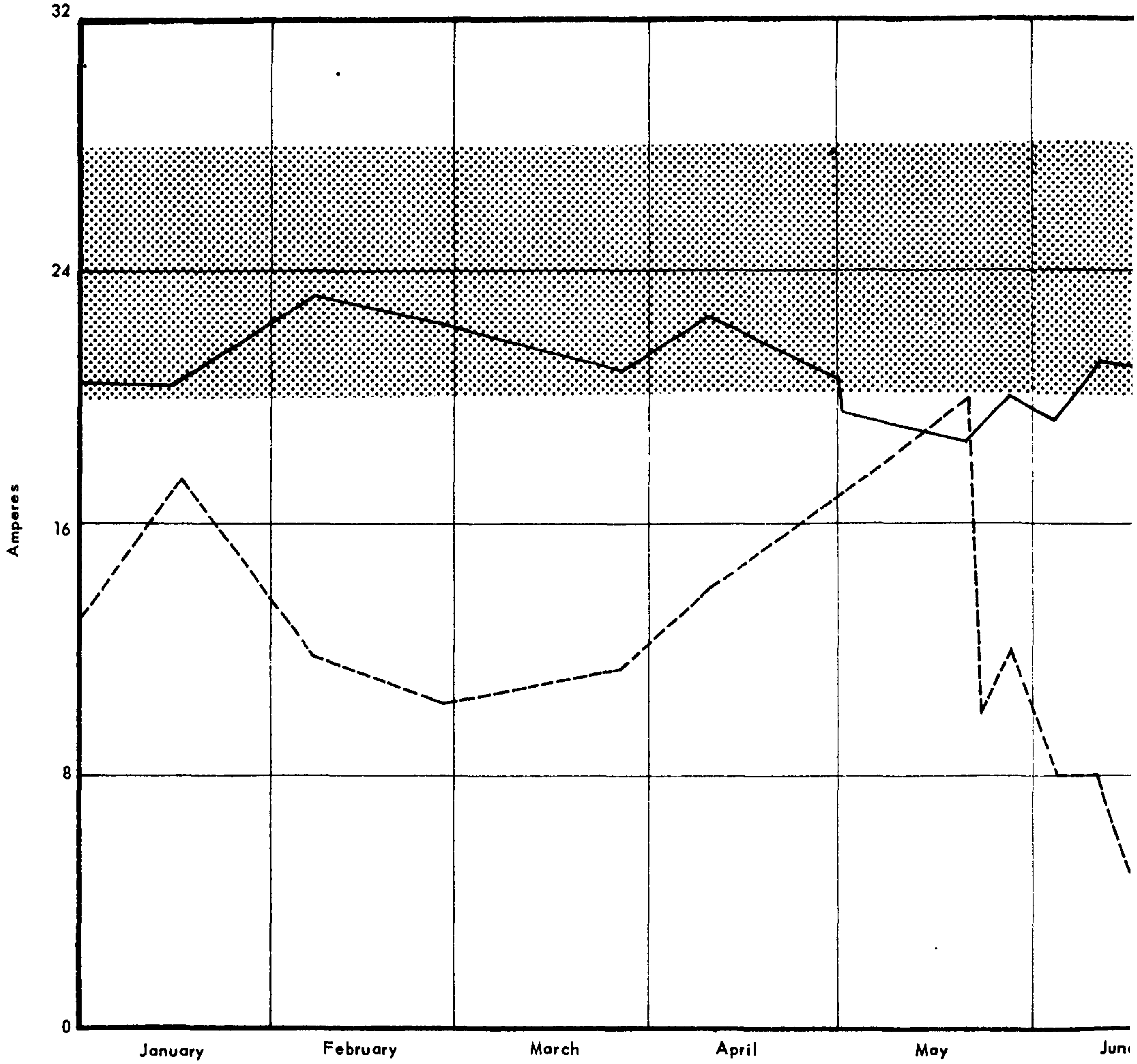


Figure 12c. Current and polarizat

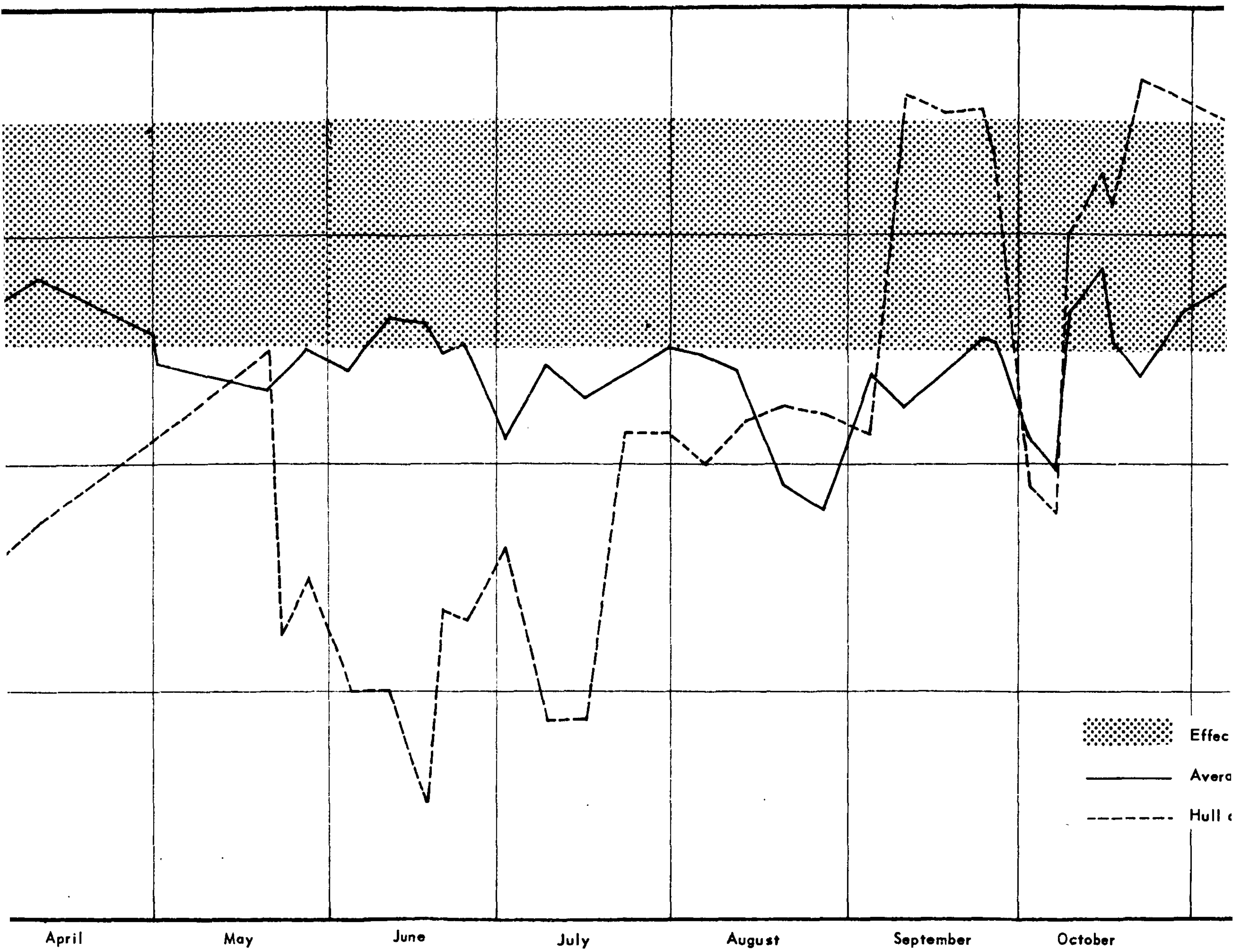


Figure 12c. Current and polarization records for 1956 for typical AFDB-4 section.

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ation records for 1956 for typical AFDB-4 section.

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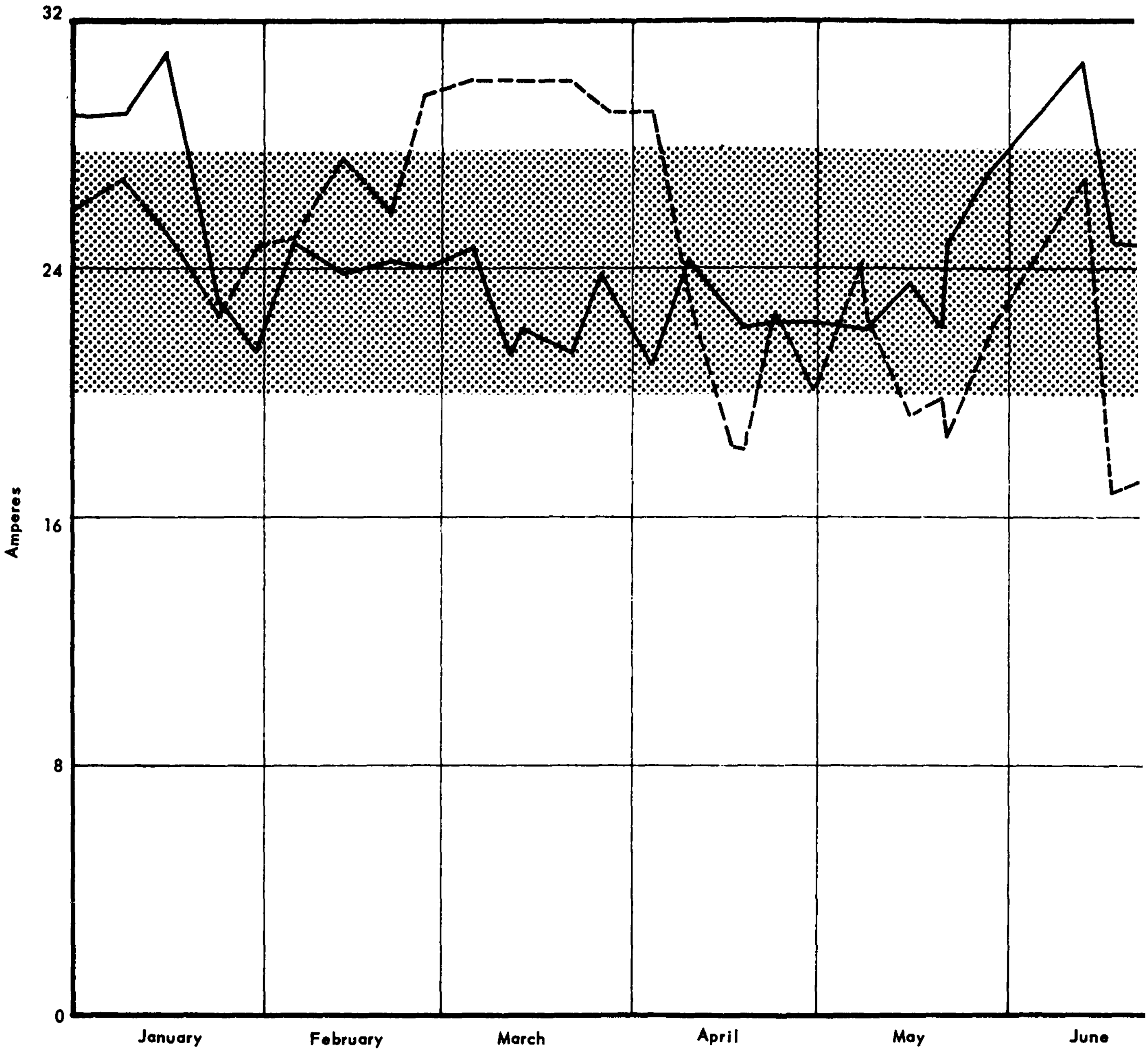


Figure 12d. Current and polarization

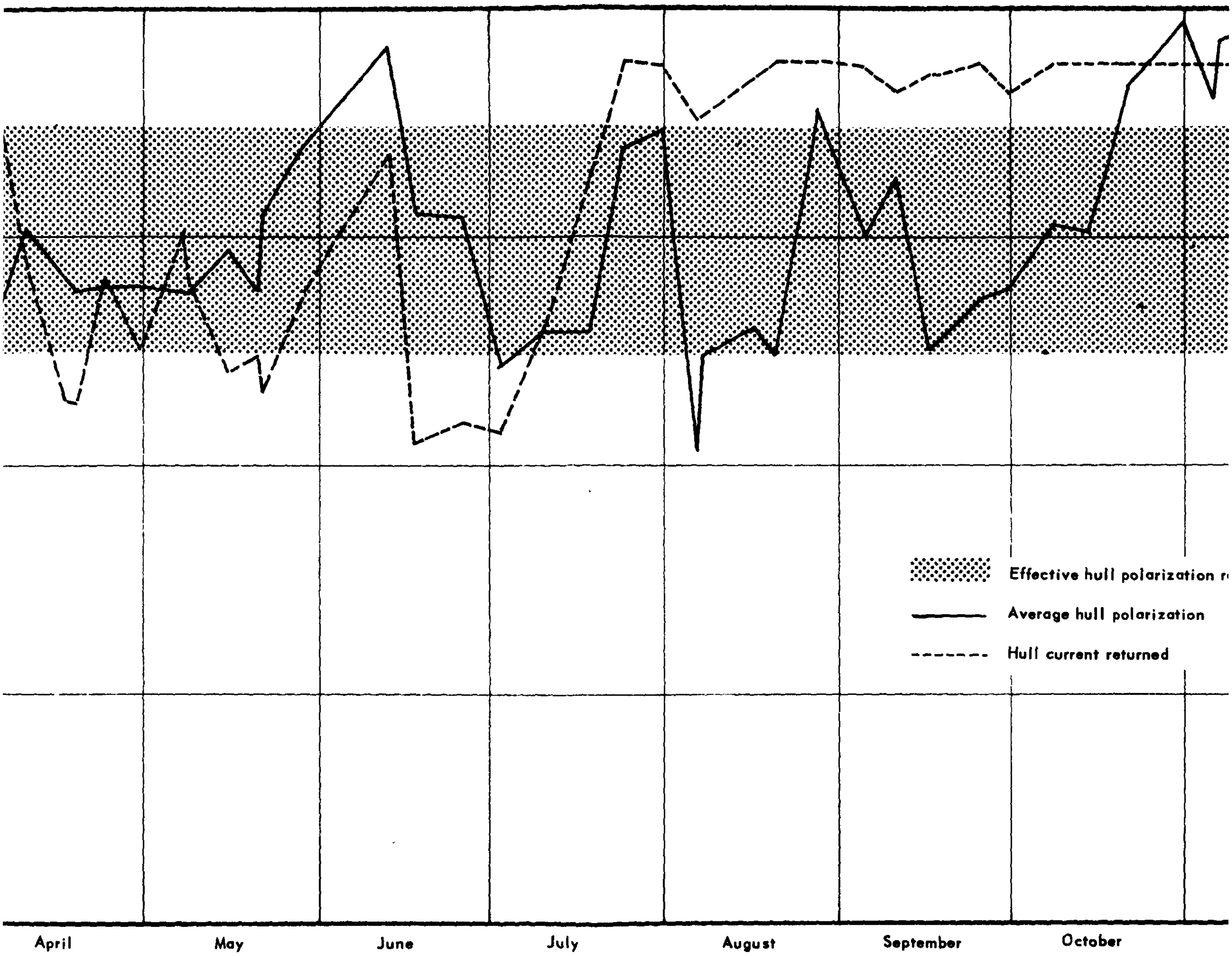
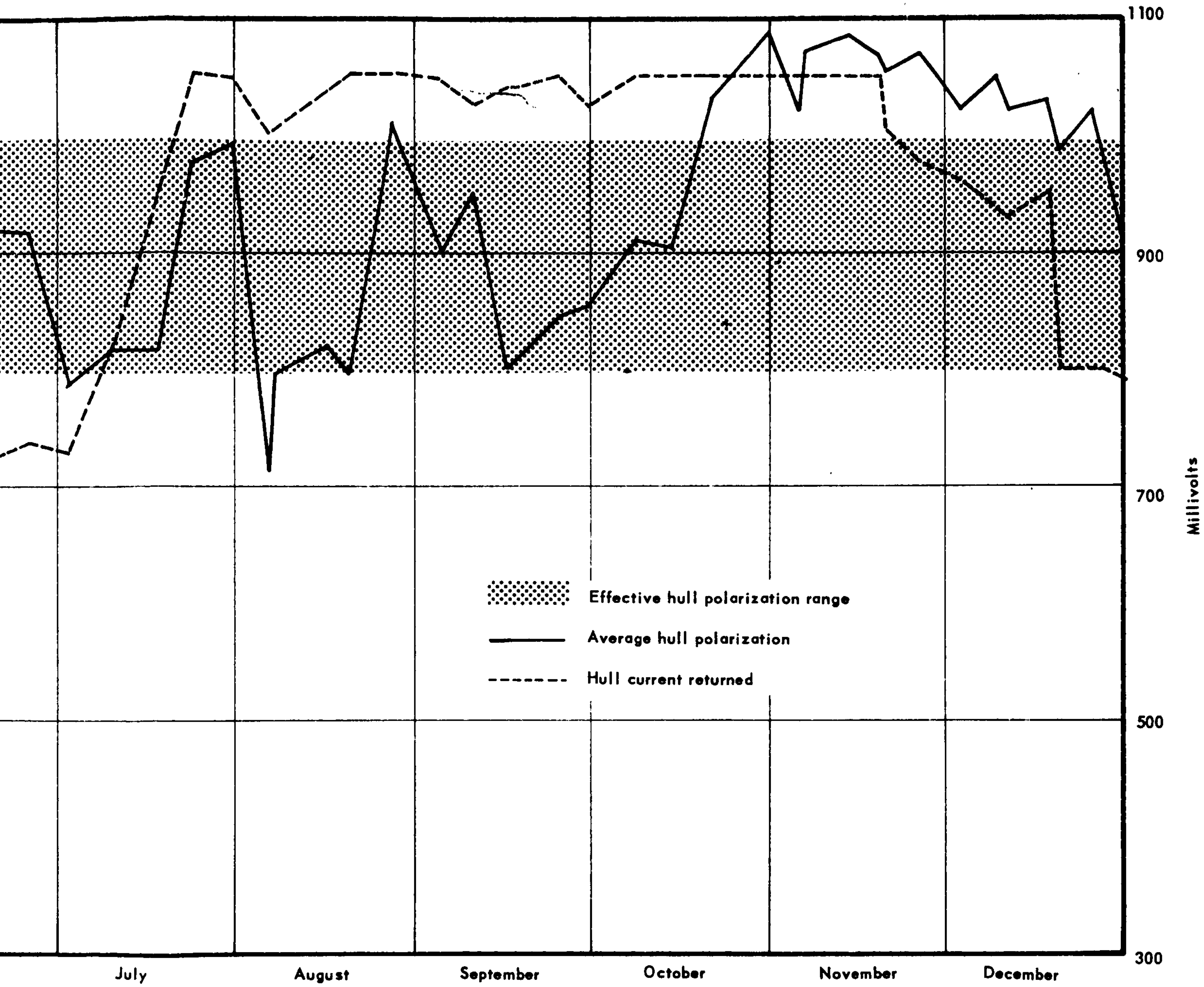


Figure 12d. Current and polarization records for 1957 for typical AFDB-4 section.



on records for 1957 for typical AFDB-4 section.

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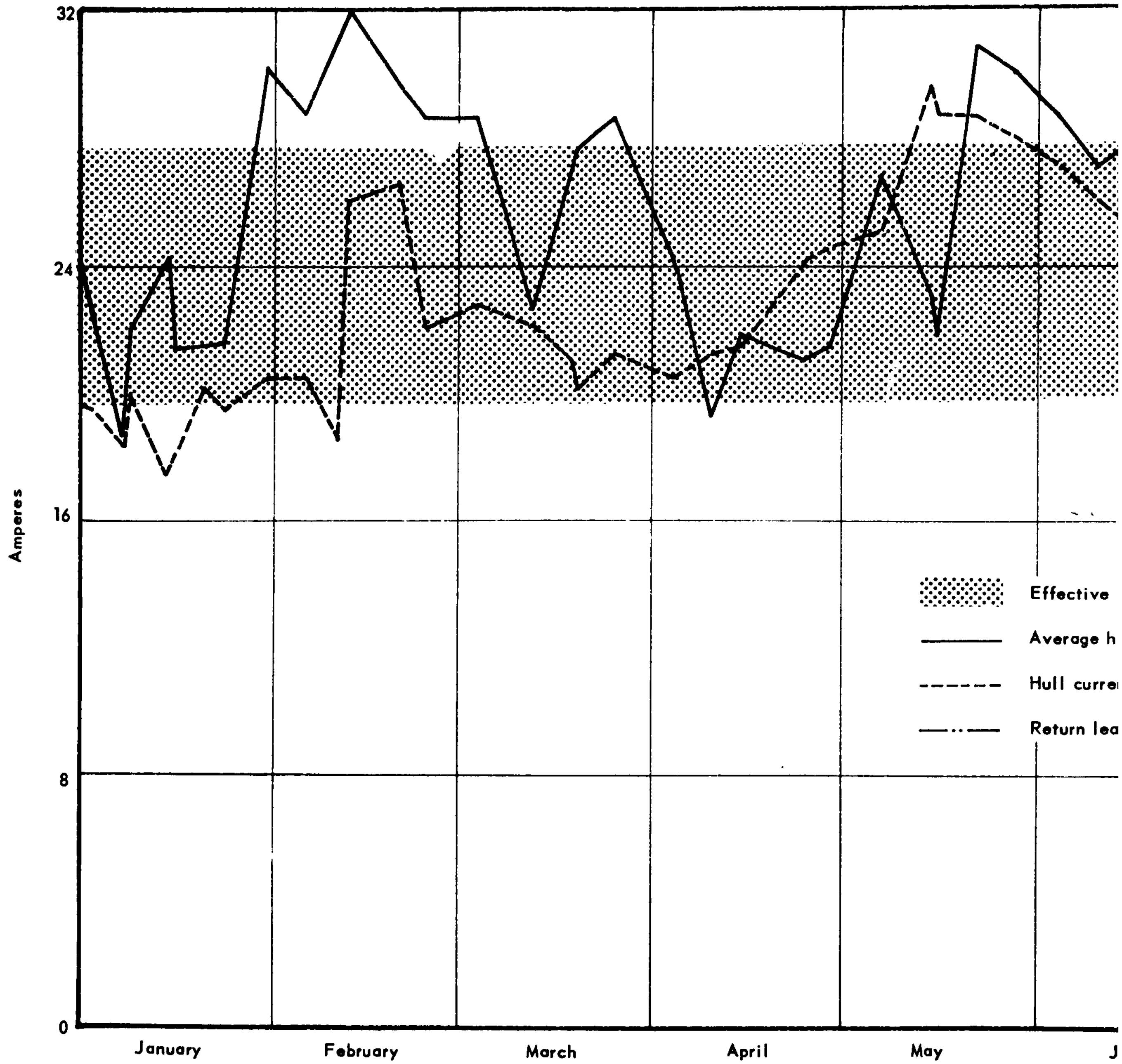
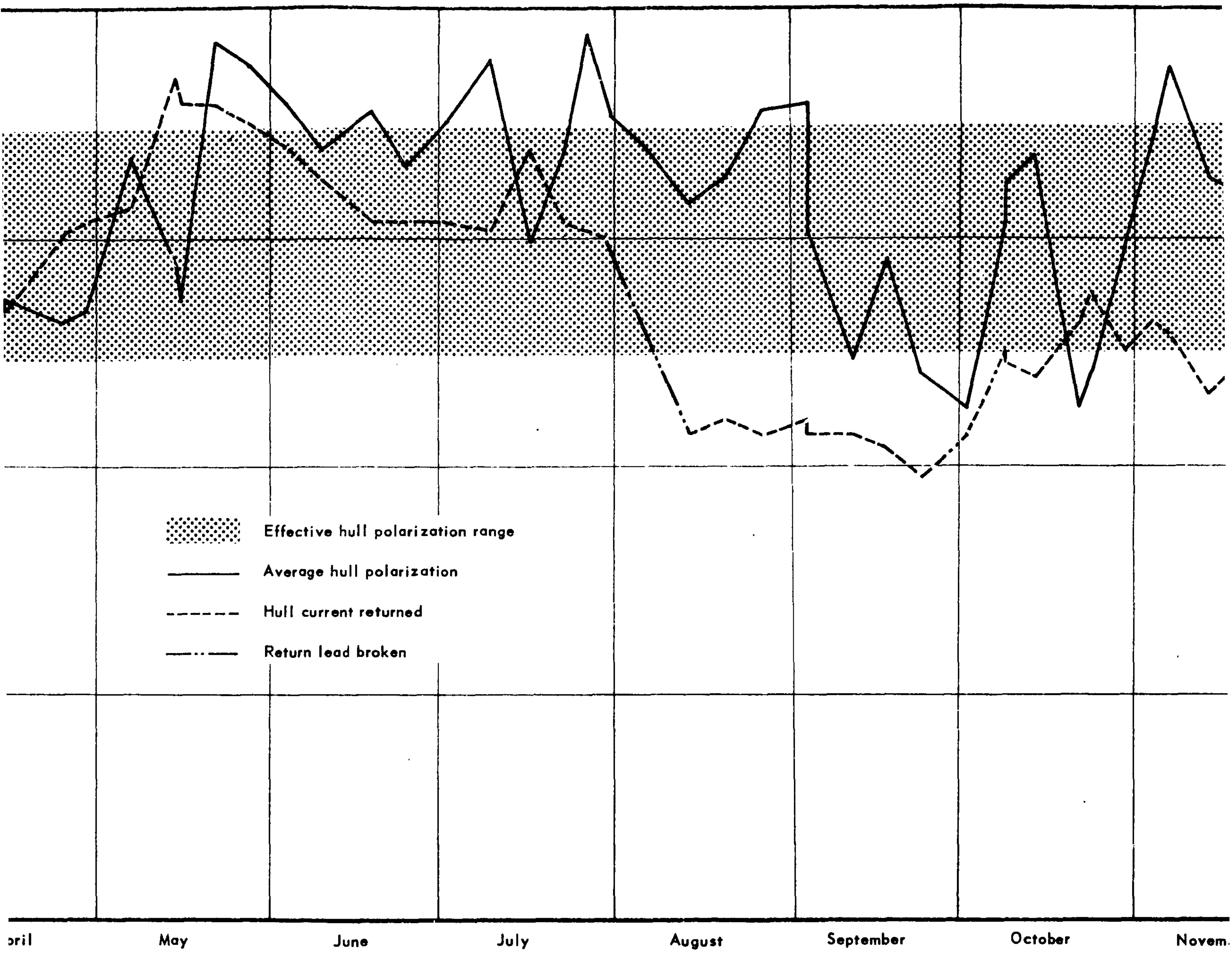


Figure 12e. Current and polari



;ure 12e. Current and polarization records for 1958 for typical AFDB-4 section.

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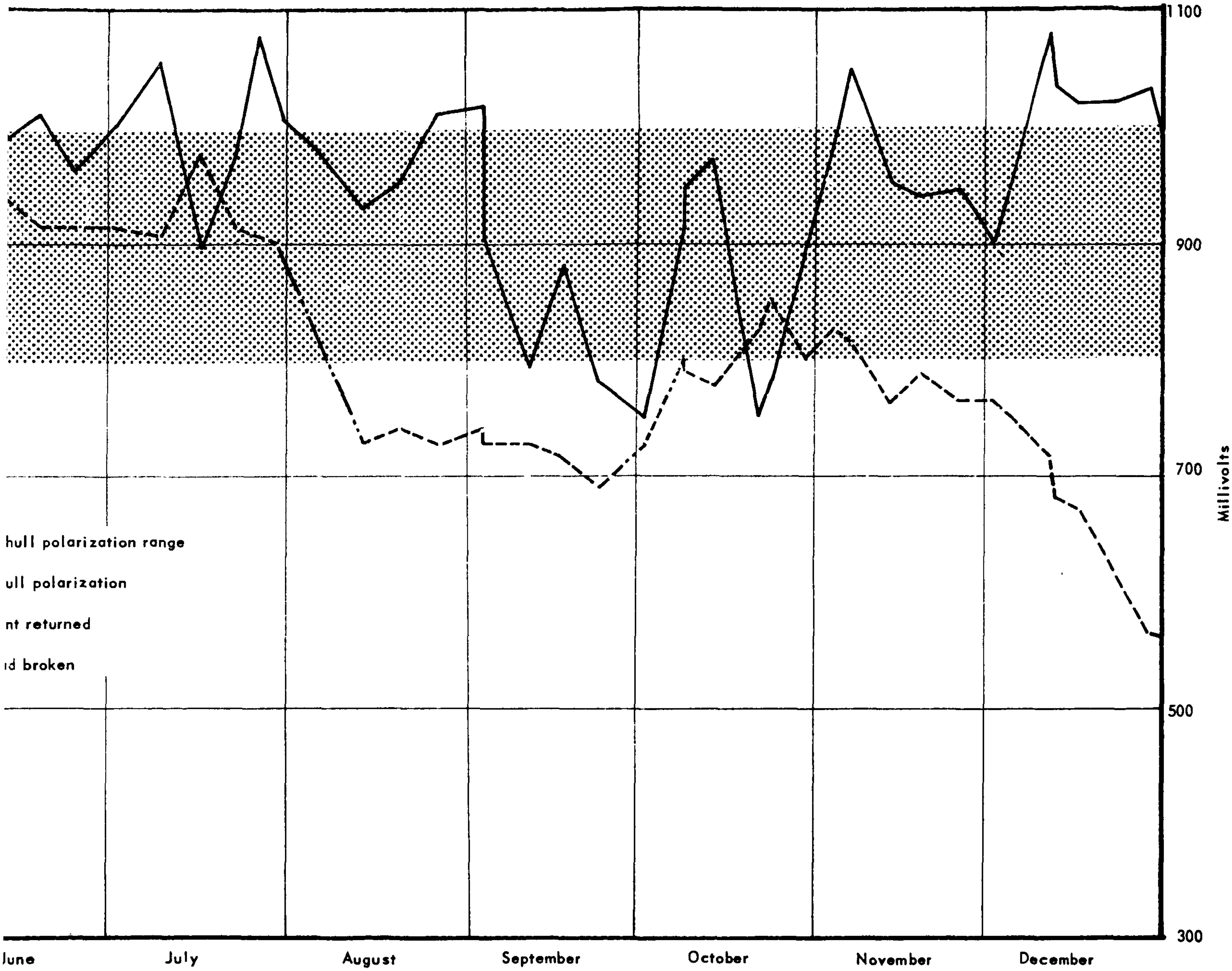

.zation records for 1958 for typical AFDB-4 section.

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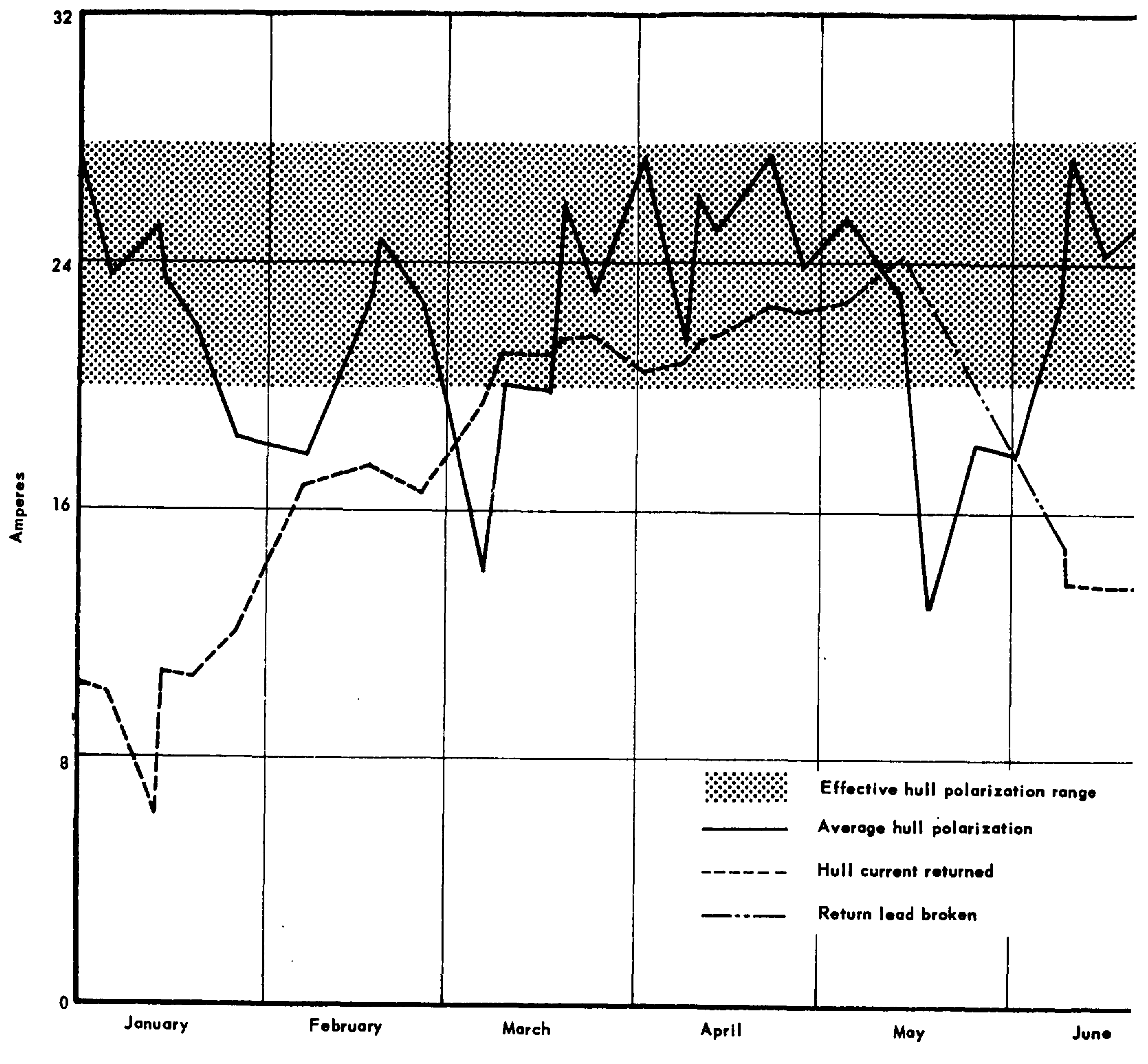


Figure 12f. Current and polarizati

1

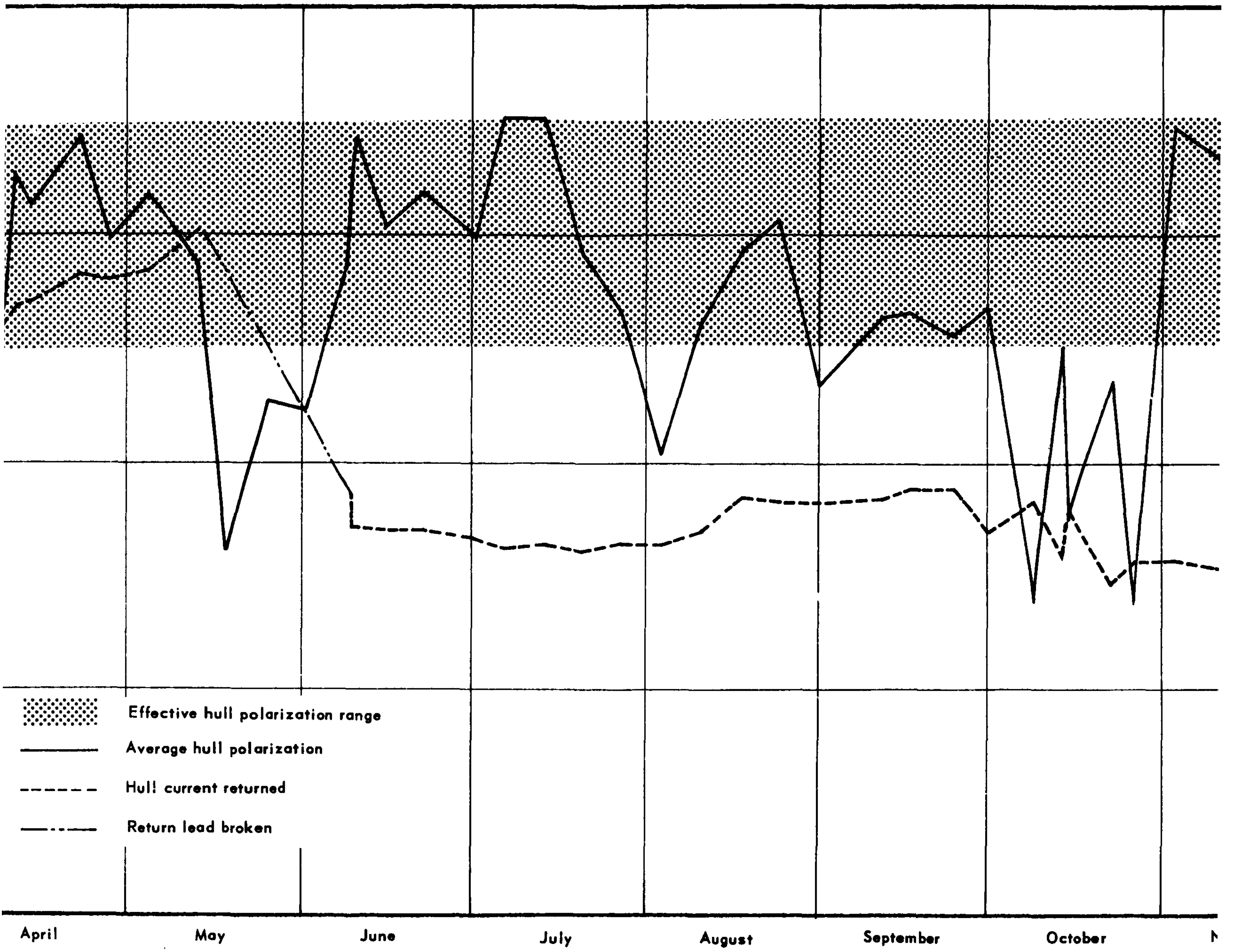
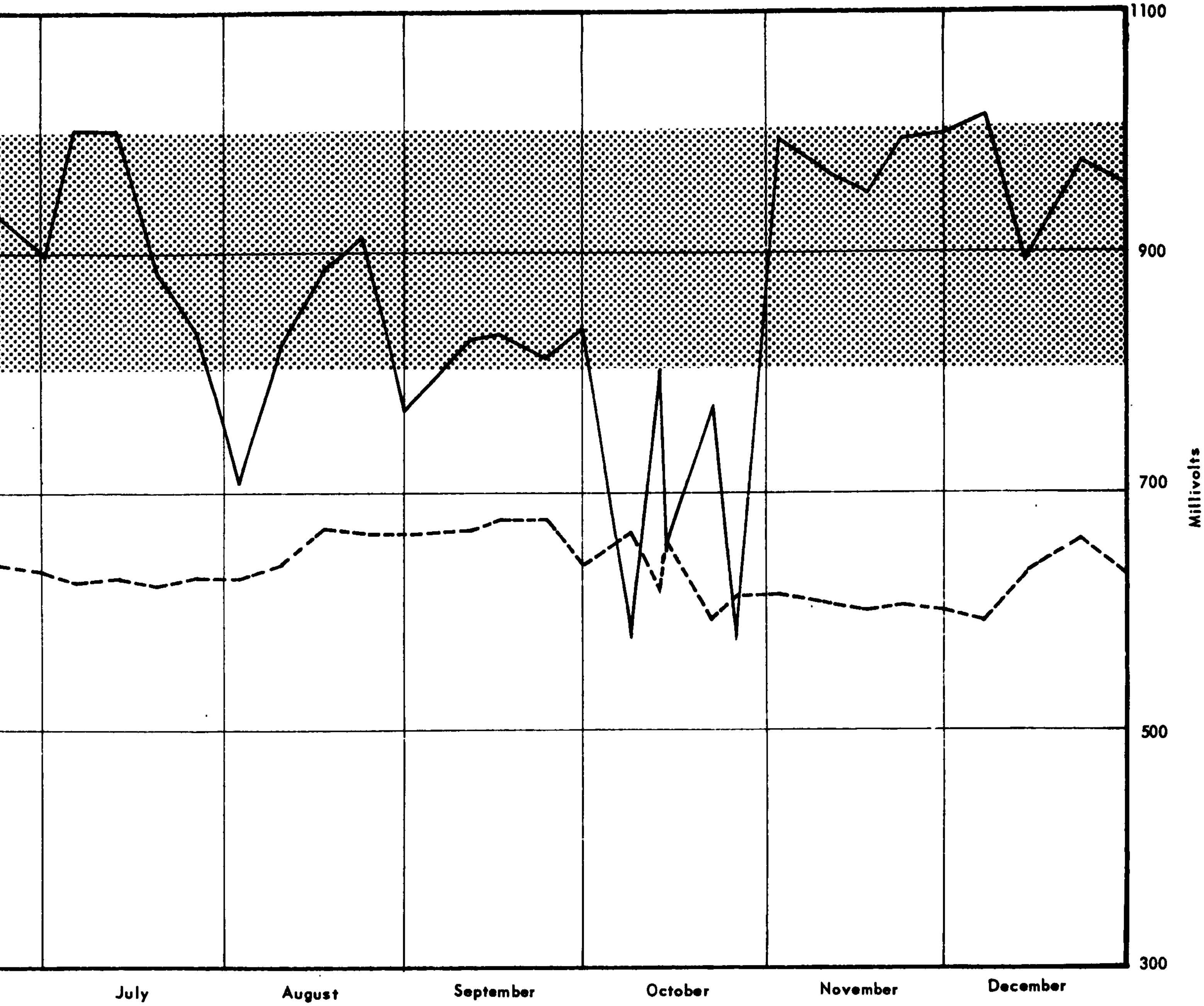


Figure 12f. Current and polarization records for 1959 for typical AFDB-4 section.

2



n records for 1959 for typical AFDB-4 section.

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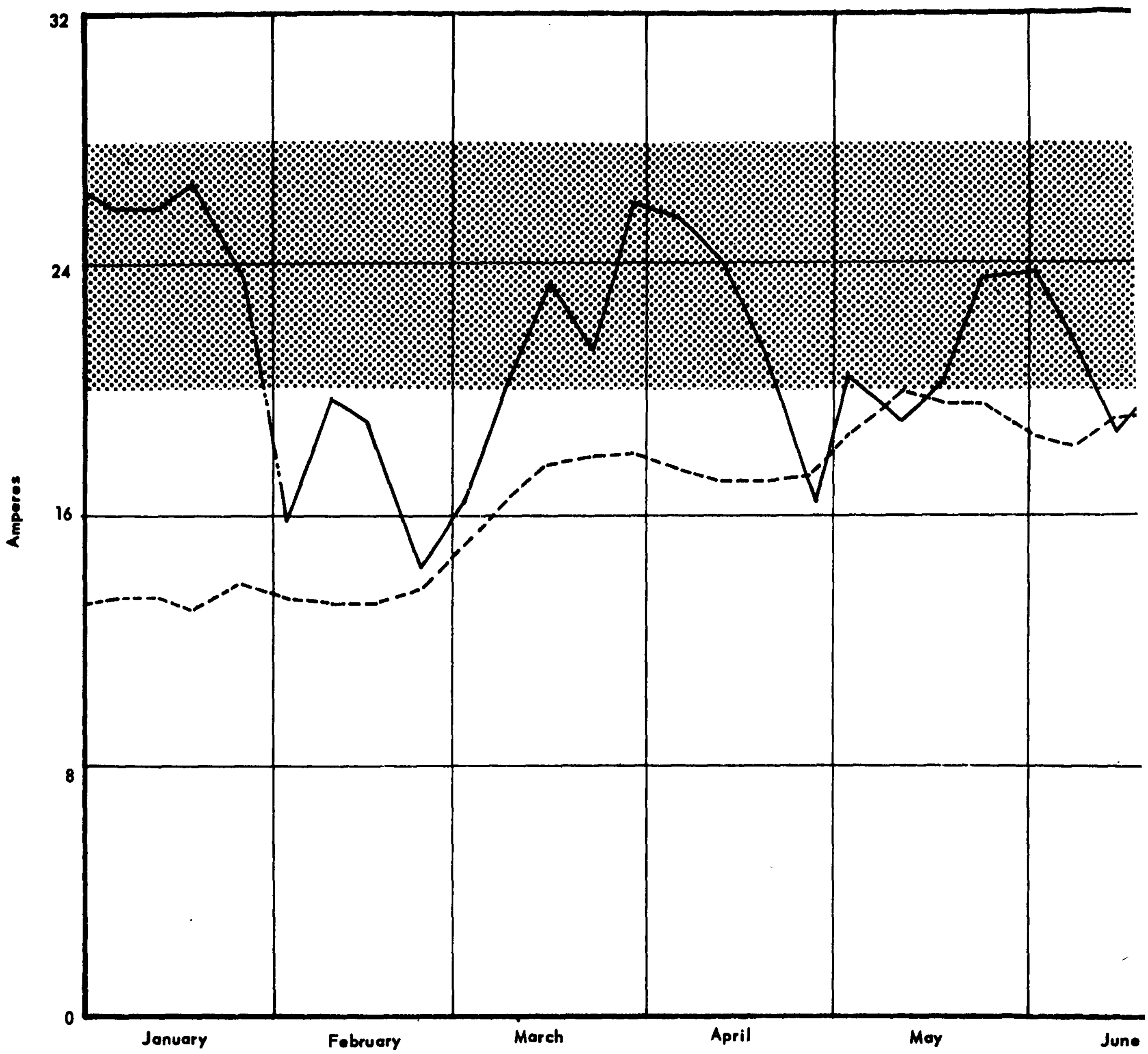
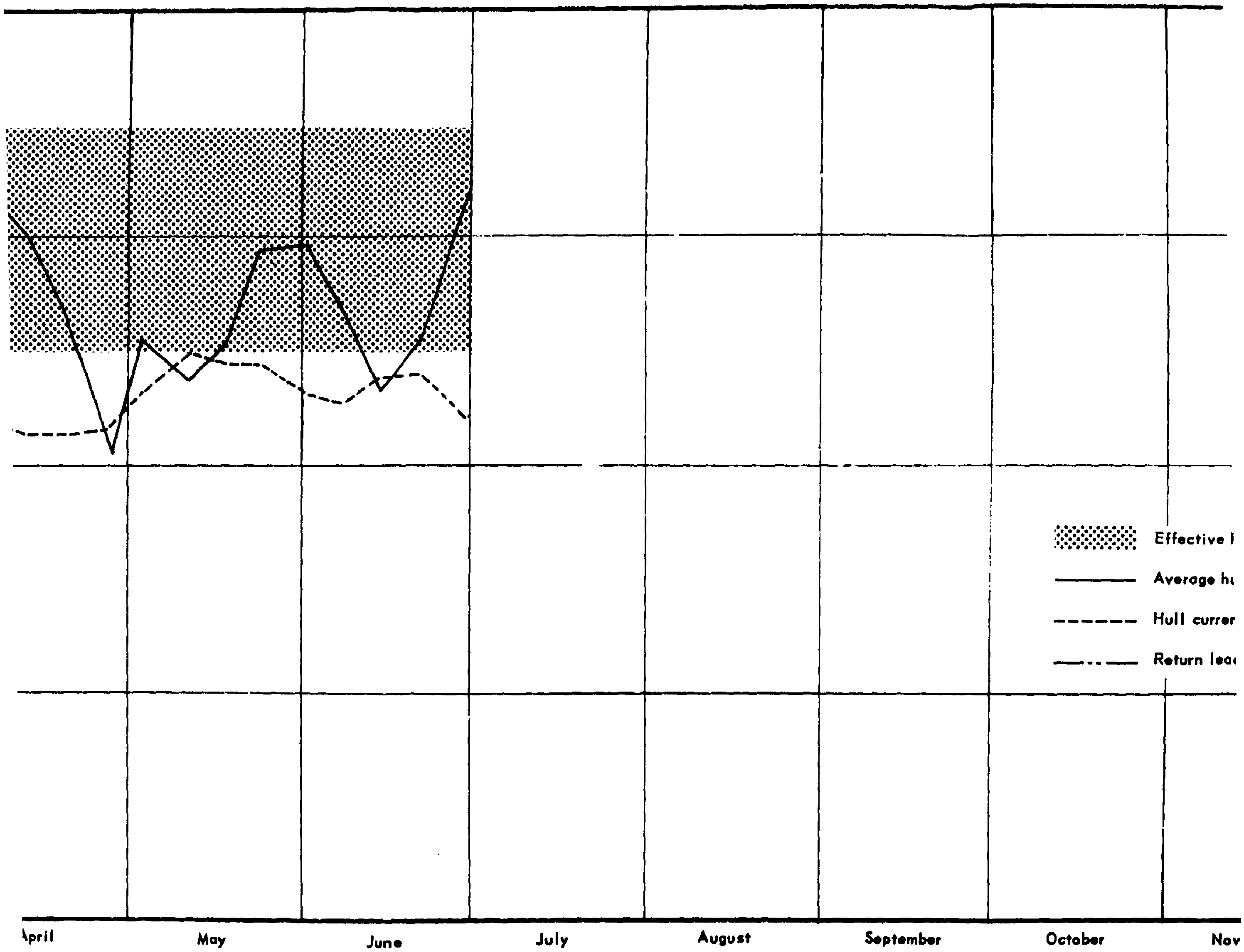


Figure 12g. Current and polarization



re 12g. Current and polarization records for 1960 for typical AFDB-4 section.

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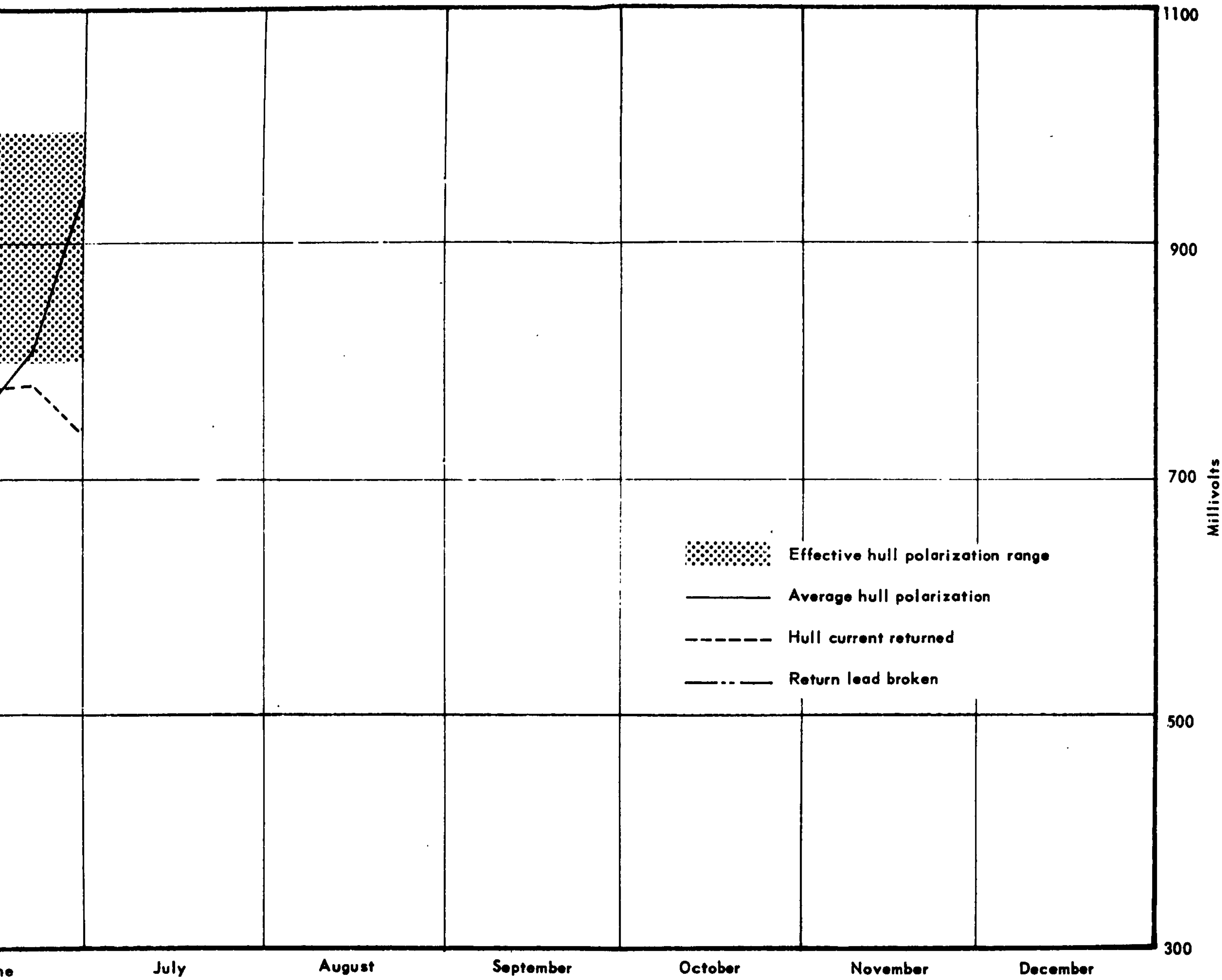


on records for 1960 for typical AFDB-4 section.

3

Documentation of the effectiveness was to be provided, as has been noted, by comparison of sets of photographs and hydrostone molds of specific hull areas, and by the change in weight of steel coupons attached to the separate hulls. Because of fiscal limitations, it was not possible to drydock any of the AFDB sections as had been planned, and the confirming data could not be obtained. The Bureau has directed discontinuance of work on this task.

ACTIVE DRYDOCK STUDIES

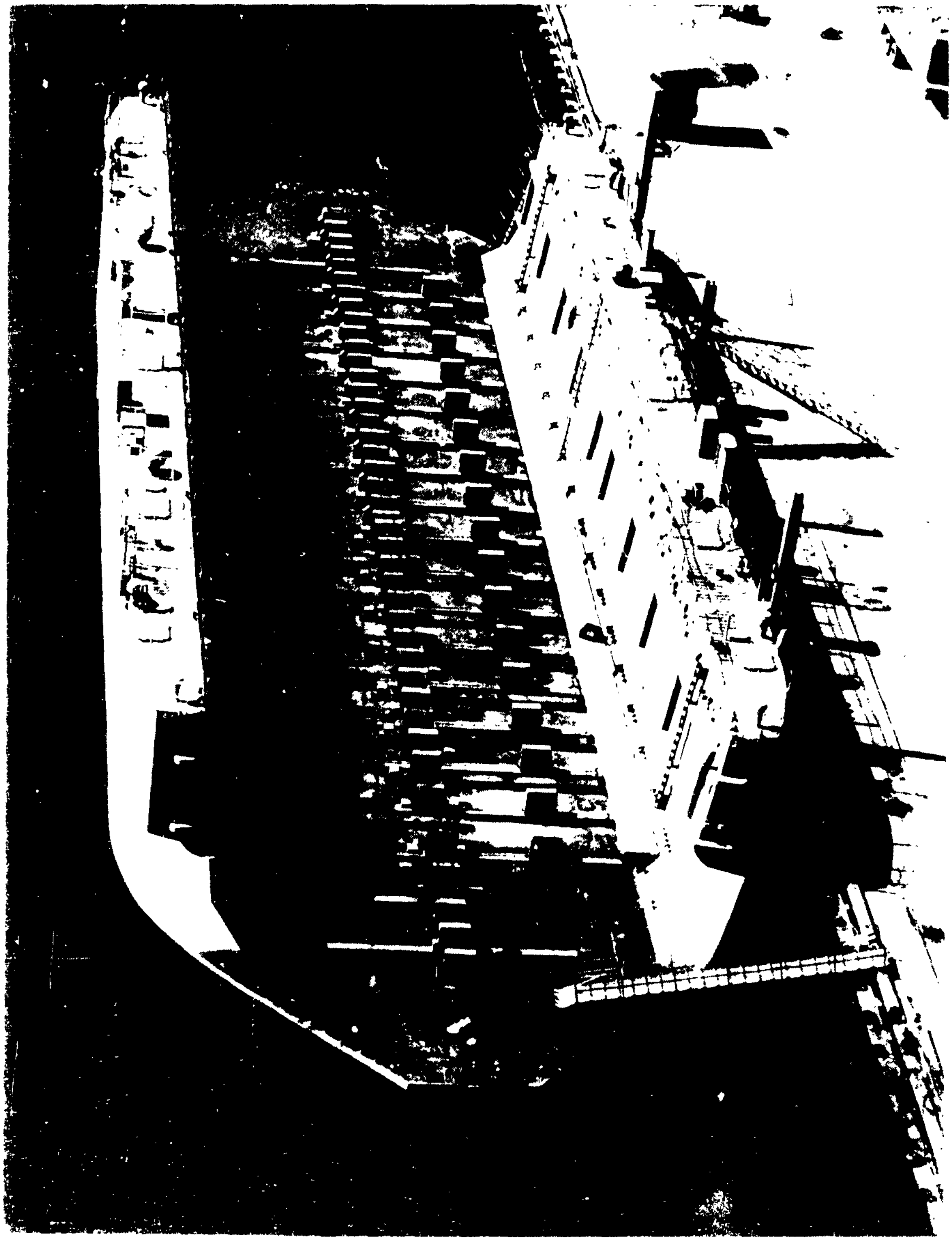
AFDL-20 Magnesium Anode System

Work on the AFDL-12 established the requirements for protection of an AFDL-class drydock by an impressed-current cathodic-protection system. It was desired to compare that system with a galvanic anode system by considering effectiveness, costs of installation and materials, and ease of operation.

Figure 13 shows the AFDL-20 which was an active drydock in Port Hueneme Harbor; it was selected as the test vessel. Magnesium anodes having an iron pipe core were used to provide the necessary current. The pipe core was attached to a length of lead wire, which in turn was connected to the drydock hull. Initially, four anodes, weighing 51 pounds each, were placed as shown in Figure 14. Within two days the polarization had reached 1100 mv, so anodes 2 and 3 were removed and the rise in polarization was checked. Eight days later, anode No. 4 was removed and the polarization was maintained at 900 mv; six months later, No. 4 was replaced and anode No. 1 was removed.

In addition to the anodes, four metal coupons were placed in the system, as shown in Figure 14, about a week before anode No. 4 was replaced in the water. Coupons 1 and 2 were bonded to the hull, while 3 and 4 were insulated. Each coupon had an effective area of about one-half square foot. Corrosion of the protected coupons was reduced to about 20 percent, and, in general, agree with Long Beach coupon data; both are presented in Table 1. The greater loss with the galvanic system was not attributable to any fault of the magnesium; it was the natural consequence of the method used to control polarity.[6] The point to be noted is not that there was an apparent difference in effectiveness, but that both methods were highly successful in reducing the corrosion of bare steel.

A preliminary estimate was made of the cost of a galvanic (active) system compared to an impressed-current (passive) system. The estimate indicated that the galvanic system would cost about $285 for a five-year period, whereas the impressed-current system would cost $420. Equipment and materials in the latter system were estimated to have a residual value of $200 at the end of the period, but the galvanic system would be completely expended.[3]



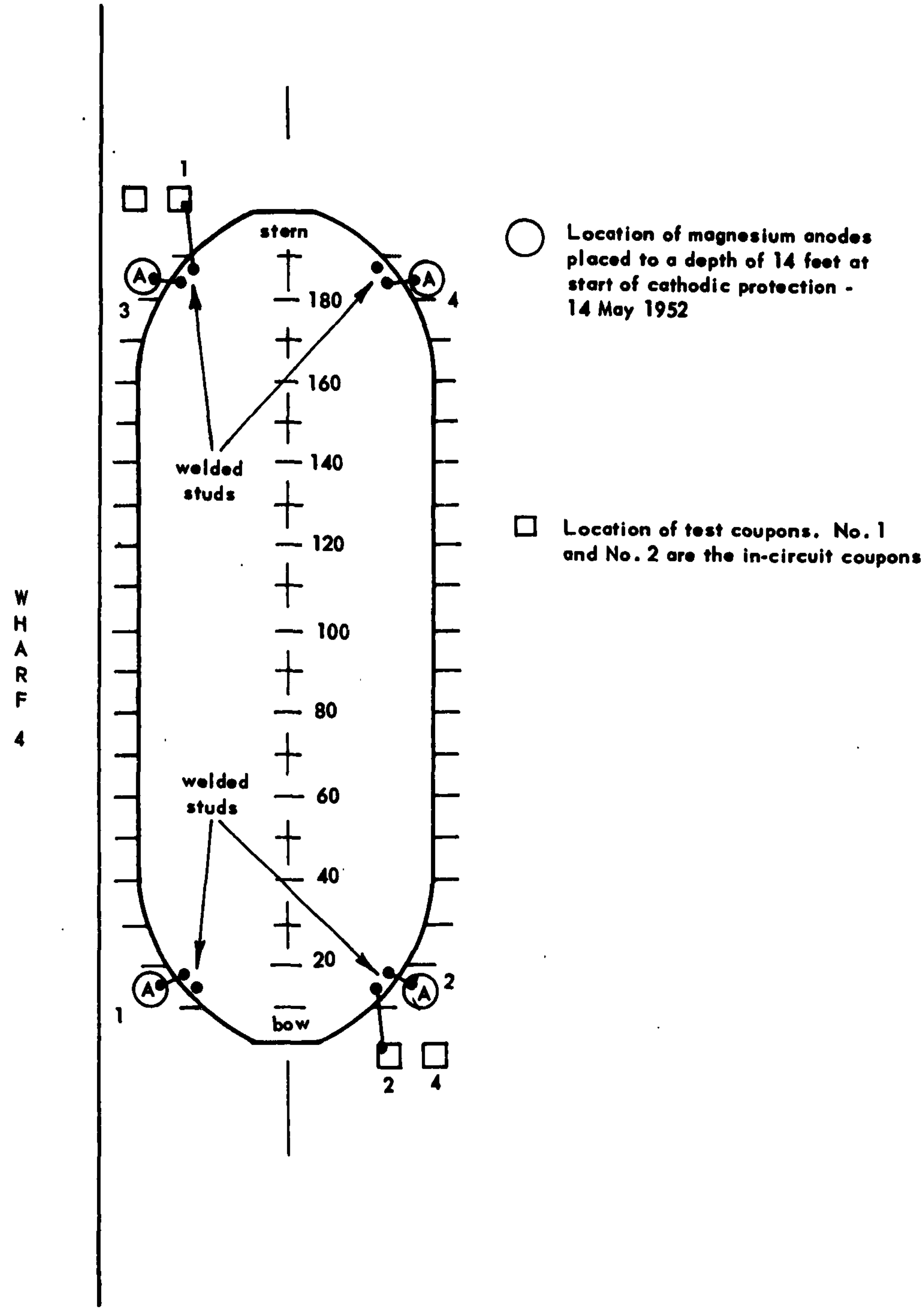


Figure 14. Diagram of AFDL-20 cathodic protection system.

The AFDL-20 system was maintained by adjusting the position and number of installed anodes after each regular monitoring survey was made. Initially no control devices were used with these anodes, and control was obtained by removing or replacing the bow and stern anodes. That method and the varying amount of submerged surface during normal operation of the drydock resulted in great fluctuations of the hull polarity. A rheostat and shunt were connected in series with each anode to permit varying the current produced and to maintain the proper polarization as the hull was raised or lowered.[6]

Addition of controls in the anode leads simplified the problem of current control. It made fine adjustments possible, rather than the massive changes in current brought on by removal or addition of anodes. However, the basic difficulty remained: every time the drydock was raised or lowered the controls had to be changed. Such continual monitoring and adjusting was not feasible, and the controls were set so that the hull polarity at minimum draft would not exceed 900 millivolts. Two anodes with the necessary controls were replaced at alternate corners of the hull, and the peripheral variation in polarity could be maintained within a 30-mv range.

It was noted that the magnesium anodes began to erode rapidly in the vicinity of the iron pipe core as soon as the core became exposed. A number of coatings were applied to the anodes to minimize or eliminate this erosion. Of the coatings tried, a thermoplastic adhesive and a synthetic-rubber adhesive appeared promising. However, some undercutting of the adhesive occurred in the normal deterioration of the anode, so if a coating is used, provision should be made for its maintenance.[3]

AFDL-20 Zinc Anode System

The overpolarization that can occur with an impressed-current system or with a magnesium-anode system may result in loss of paint due to blistering. When the manpower situation is such that optimum conditions cannot be maintained, some system with an inherent limit should be used. One material for such a system is high-purity zinc. It has a low open-circuit potential, high current efficiency, and is fairly low in cost.

A zinc-anode cathodic-protection system was designed for the AFDL-20. Calculations indicated that six anodes, equally spaced around the hull, would provide adequate protection. Each anode weighed 60 pounds, was 60 inches long, had a 4-square-inch cross-section and was cast around a 1/4-inch threaded-end galvanized-steel rod. Electrical cable was connected to both ends of each anode as shown in Figure 15; connection to the hull was made through a combination support and electrical lead cable. Shunts of 5-amperes capacity and 0.01-ohms resistance were included in each circuit to permit monitoring the current.

Figure 15. Completed anode connection with Neoprene covering.

The system was first installed in April of 1955; it was soon noticed that the hull polarization was increasing very slowly, so magnesium strip was added to the system. The polarization increased rapidly to almost 1000 mv, but gradually decreased to 770 mv after the magnesium was consumed. Since the boot-top area was to be repainted, no extra anodes were added. When the boot-top reconditioning was completed, the current requirement dropped from 14 to 5 amperes, and the average polarization increased to around 900 mv. Two test coupons had been coupled to the hull for 8 months; when they were removed and weighed, the losses were 0.38 and 0.23 mpy as compared to the previously determined 5.2 and 6.6 mpy from unprotected coupons.[7]

In 1955, when the Bureau was advised that the AFDL-20 was to be drydocked for hull reconditioning they requested the Laboratory to conduct a special investigation of the hull. The drydocking began in January 1956, about 3-1/2 years after cathodic protection was first installed. Originally the dock was painted with Formula 15 hot plastic up to the 2-1/2-foot draft level and with Formula 145 cold plastic from there up to the 5-1/2-foot level. In August 1955, the area between 3- and 9-foot draft was sandblasted and repainted with Formula 145. This was the boot-top reconditioning already mentioned.

The inspection revealed that less than one percent of the Formula 15 hot plastic had failed. Areas devoid of paint were roughly circular and measured 1 to 4 inches in diameter. A number of small raised areas were scattered throughout the remaining hot plastic. When the material in these areas was removed, the undercoat was found to be absent.

The original Formula 145 cold plastic was less effective in corrosion and fouling prevention than the Formula 15. The recoating in the boot-top area had deteriorated to an unusual degree. Possible causes of the failure could have been: (1) inadequate surface preparation, (2) storage effects on the properties of the coating, and (3) application of the coating under unfavorable conditions. The surface had been sandblasted and presumably adequately prepared. The paints used were in storage for several years and may have deteriorated. The actual application was accomplished with the dock in the water; the humidity had an adverse effect on the performance of the paint. The inspecting party observed that the decrease in deterioration was more or less proportional to the distance from the waterline at the time of reconditioning.

The inspection party recommended that the hot plastic be extended to the 5-1/2-foot level; this was incorporated into the final paint system. Development of a more durable coating for the boot-top area was also recommended.*

When the original six zinc anodes were removed prior to drydocking the AFDL-20, a thick porous coating was observed on all the anodes. When the reconditioning had been completed and the drydock moored, the coating was brushed off three of the anodes. The other three were left as they had been found and all six were reinstalled. Immediately after immersion the current output of the cleaned anodes was about double that of the unbrushed anodes. After 5 days, however, there was essentially no difference in the output.

After reconditioning, the current requirement decreased from 8.45 amperes at 827 millivolts to 2.06 amperes at 1015 millivolts. The two amidships anodes were removed and the average polarization dropped by 50 millivolts. To determine the response of the zinc to changes in potential, the draft was increased by 14-1/2 feet; the polarization rapidly dropped to 712 millivolts but within an hour had increased to 800 millivolts.

Over a three-month period, with the hull at normal draft, the average potential gradually decreased to 800 millivolts. The two anodes previously removed were returned to service. The current output of all anodes gradually decreased as the anode material was consumed, and the maintenance

* NCEL. Ltr report R-010, Inspection of the Exterior Hull of Floating Drydock AFDL-20, by E. R. Streed. Port Hueneme, California, March 1956.

of adequate protection was not possible. New anodes were bolted to the original suspension system in all six locations and the potential increased to the protection range.

The total cost of the zinc-anode system was $363; this included shunts, terminal boxes, extra cable, and labor necessitated by the nature of the investigation. A non-experimental system would cost about $220; this would cover only the materials and labor to provide a working system. These estimates are all for a two-year period; subsequent costs would be for replacement anodes and the labor and materials to replace them.

YFD-70 Floating Drydock

Operated by the Bethlehem Steel Company at their San Francisco shipyard, the YFD-70 was given a thorough inspection by Ebasco Services, Inc. of New York, during May and June of 1958, to determine the extent of the corrosion of existing surface coatings. Ebasco reported accelerated corrosion of bottom plates in several compartments; this generally appeared as grooved and circular pits. However, there was little corrosion in the remainder of the ballast compartments. Ebasco recommendations included a zinc-anode cathodic-protection system for underwater areas and further application of a corrosion-preventive grease compound to the intermittently wet areas.[8]

Additional floating corrosion inhibitor was added. An experimental zinc-anode cathodic-protection system was installed in Ballast Compartment No. 8, which had suffered the most bottom corrosion. The cathodic-protection system consisted of 44 zinc anodes placed in 11 rows of 4 anodes each. The rows were perpendicular to the inner bulkhead, and were evenly spread out between the end bulkheads. Each anode measured about 6 inches by 12 inches by 1-1/2 inches. Of each group of four anodes, the first was welded to the inner bulkhead by cast-in straps. The second anode was welded to the second longitudinal stiffener, and placed above the stiffener with its largest surfaces parallel to the inner bulkhead. The third and fourth anodes were welded to the fifth and ninth stiffeners, respectively, in the same manner as the second anode. After very few months those anodes had become passive through the formation of a hard coating. They were replaced by an equal number of similar anodes made of a low-iron zinc alloy.

By the time of the inspection, the new anodes had been consumed evenly, as had those in corresponding positions in each group. The degree of consumption increased with the distance of the anodes from the inner bulkhead; the average consumption was somewhat less than 5 percent.

Corrosion in the lower portions of Compartment No. 8 was nonexistent; only the results of previous corrosion were seen. The upper areas of the compartment had some rusting, but it did not appear serious.

Other sections entered included Ballast Compartments Nos. 6 and 9, as well as Wing Wall Tank No. 10 and two wing wall compartments identified as Nos. 32 and 46. Except for No. 8, all of the ballast tanks showed appreciable corrosion. Many of the rusty streaks observed were examined down to bare metal; there was no evidence of localized corrosion. A number of the streaks were found to be in line with welding done on the other side of the bulkhead separating the main and wing wall compartments. Scaling was general but not heavy in the upper parts of the main compartments; this may have included part of the original protective coating.

The lower portions of wing wall and main compartments of Ballast Tank No. 10 were not heavily rusted, although corrosion was evident. Localized corrosion occurred on the bulkhead which separated the two compartments; one pit was estimated to be 1/16-inch deep. Several welds were examined and some showed accelerated corrosion. Pits adjacent to the weld bead resembled those described in the Ebasco report, but were also typical of the undercutting which may accompany improper welding.

In the wing wall portion of No. 10, rusting was more general, but there was less incidence of local corrosion. Extreme scaling was observed in the upper areas of the wing wall. Although there were traces of what may have been the corrosion inhibitor in this area, there was no evident penetration of the compound to the metal surface. A similar situation, but to a greater degree, existed in the upper portions of Nos. 32 and 46. Rust on the walls was in the form of large sheets which could be removed in thicknesses of 1/4-inch. Possibly these two sections, which formed part of the overhang of the center section of the drydock, were never adequately treated with the inhibitor.

Another possibility is that solar heat made the steel deck and walls much warmer than the atmospheric temperature, causing softening of any thickened inhibitor on the walls, allowing it to flow, and resulting in accelerated corrosion. Corrosion was less near the compartment bottom.

A certain amount of corrosion rust or rusty streaks was common to all openings in bulkheads and stiffeners. The Laboratory representative made no measurements of the thicknesses of frame members or stiffeners, of pit depths, or of the present size of the zinc anodes. Personnel of the San Francisco Naval Shipyard were taking Audigage readings of various areas on the drydock. A report of their findings was to be made to the Bureau of Ships.

The general effectiveness of the zinc-anode cathodic-protection system in Compartment No. 8 indicates it is highly desirable. Standing water and silt deposit prevented adequate examination of bottom plates in the areas where a cathodic protection system would be most effective. However, rust in the other compartments would indicate continued corrosion of the bottom plates. It is understood that Bethlehem Steel is extending the zinc-anode cathodic-protection system to include all the main ballast tanks.

It is difficult to apply inhibitors to ballast tank inner surfaces because they are so far from the sprayer. The lack of color contrast between flotation-type inhibitors and the interior of the tanks makes it impossible to judge coverage. Perhaps some inert coloring agent could be added to the inhibitor.

Many of the inhibitors are supposed to penetrate surface rust, but the 1/4-inch layer existing in several sections is too thick. Therefore, all loose rust scale should be removed and a corrosion inhibitor should be applied to all ballast tank surfaces.

It might be advisable to extend the annual inspection to include all of the upper portions of the wing wall compartments, where such extensive rusting was noted.

OTHER STUDIES

Automatic Control

Polarization records clearly show the need for an improved method for regulating protection current. Irregular inspection permits over- and under-polarization for relatively long periods. To maintain a system at optimum potential would require increased attention by competent personnel.

Some work was done on automatic controls for ground installations prior to 1954, but no references were found to similar work for sea water systems. Among the problems which existed were the magnitude of potential and the constant measurement of the hull potentials. Although several standard devices were available for potential measurement, their service life was relatively short. Commercial and Laboratory-constructed half-cells, and modifications of these, were investigated, as well as electrodes of graphite and various metals. Those showing greatest promise were silver-silver chloride and copper-copper sulfate half-cells, and electrodes of magnesium or zinc.

Figure 10 shows an amplifier and servo system for automatic control of the Long Beach installation. This was used because a complete magnetic amplifier system was not available. Development of such a system was not started sooner because of the expense; the electronic equipment for the preliminary studies cost about $200. The unit controlled the current in the Long Beach installation, and was used to investigate the various sensing elements. An electrode of high-purity zinc was found to be the most satisfactory of those mentioned above.[4]

The unit operated satisfactorily from installation and testing in late April and early May of 1954 through 7 September 1955 when it was replaced by a two-stage magnetic amplifier servo system. The newer unit was more simple and reliable; it functioned properly until 17 October 1956 when other equipment broke down. The excessive aging of the selenium stacks in the rectifier had resulted in its failure.

Negotiations had been under way for some time for the development of a complete magnetic amplifier system. Several firms had indicated their interest in designing and constructing a prototype to control the Long Beach installation. Four bids were received, and a contract was awarded to the Rheem Manufacturing Company of Downey, California, for the design and construction. The complete unit, shown in Figure 16, was installed 16 January 1957; its effectiveness is shown by the period of relatively stable polarization (in Figure 12e) following the installation. A fire of unknown origin completely destroyed the unit on 31 May 1957. Other agencies were investigating automatic control systems, so work on this phase was discontinued.

Paints and Cathodic Protection

In recent years many investigations have been made of paint systems for use with cathodic protection. Usually the test conditions were fixed in accordance with the objectives of the particular study, whether it be electro-osmosis, alkali resistance, antifouling properties, or other problems. It was concluded generally that coatings with high electrolytic resistance and high alkali resistance were desirable. Other significant factors were the thickness of film, the degree of potential control, and the effect of overpolarization on different coatings.

The sea water environment and the freedom from fouling necessary for Naval floating equipment compound the problems of developing an overall effective coating system. Coatings now in general use are not fully effective in eliminating corrosion over a long time. Although cathodic protection is effective even in the absence of any coating, such a condition would require an elaborate system for distributing current. Neither coating nor cathodic protection is the final answer; in many cases a combination of the two is to be preferred.

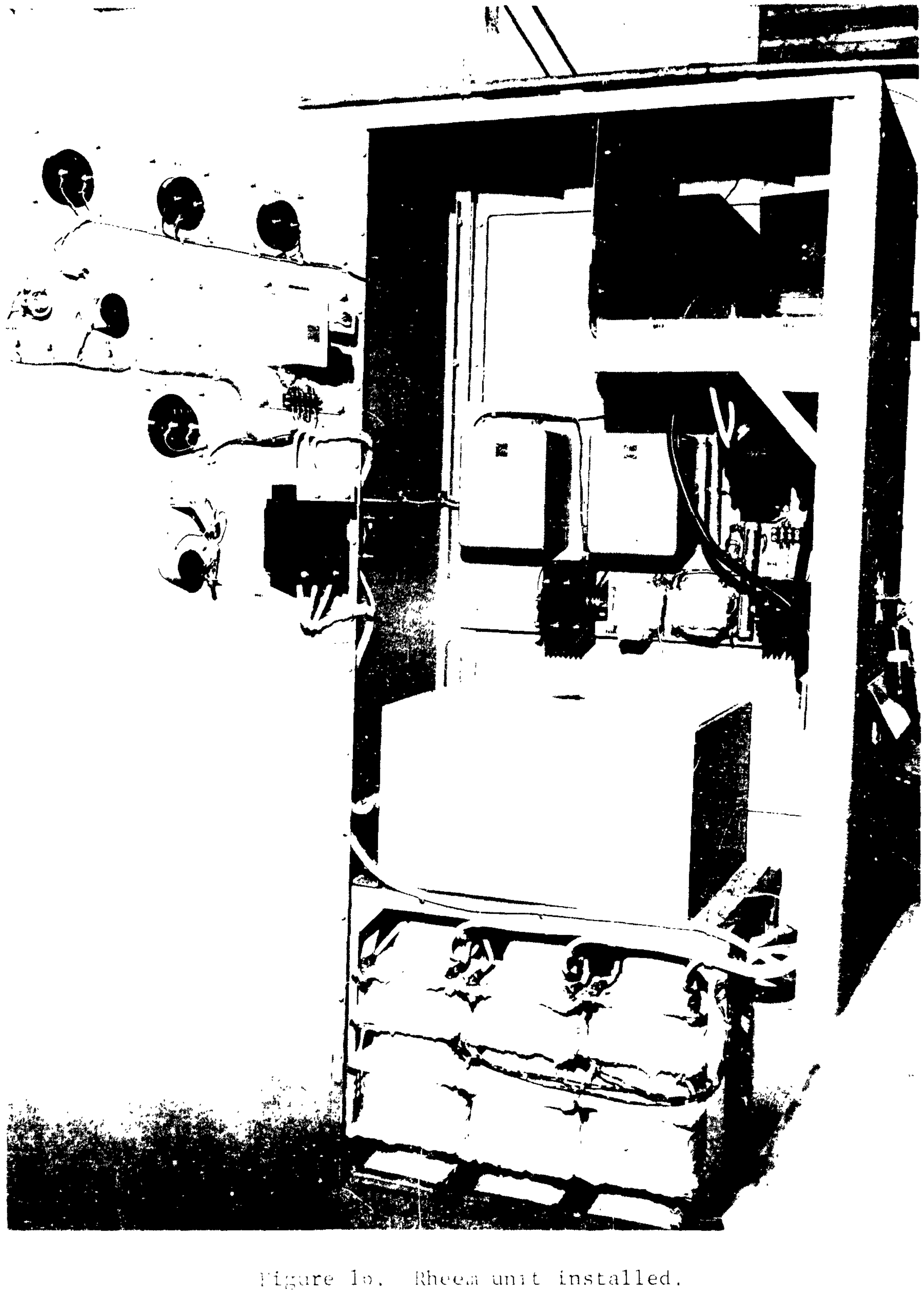


Figure 16. Rheem unit installed.

Where a floating structure will be drydocked often, a good paint system might be preferred to full-time cathodic protection. When damage to the paint began or was suspected, cathodic protection could be applied until regular hull reconditioning could be scheduled. Cathodic protection might be used when it is not practical to repaint in intervals of relatively few years. The coating in such a case should have high electrolytic resistance, since its main function would be to reduce the current requirement. The coating would be replaced when the current requirement reached a pre-determined value.

A study was initiated to evaluate 21 standard Navy paint systems and proprietary materials. Coatings were selected on the basis of BuDocks' suggestions of standard systems being used underwater, with the addition of proprietary materials which had shown promise in other Laboratory studies. Most of those selected were applied at Port Hueneme under the supervision of Laboratory personnel and in accordance with the supplier's instructions; the rest were applied at the Long Beach Naval Shipyard.

The test site was the entrance channel to the Port Hueneme harbor. Panels 4 inches wide and 6 feet long were made from 1/4-inch steel. After being coated the panels were installed in a circular floating test rack shown in Figure 17. In the center of the rack was a 3-inch-diameter by 60-inch-long graphite anode, through which the power was supplied. Potential measurements were made relative to a copper sulfate half-cell located near the center of the float. Although a negative potential of 0.85 volts was desired, the location of the float was conducive to intermittent depolarization as a result of tidal currents, waves created by passing vessels, and weather changes.

After a year the panels were classified and evaluated by their electrical resistance and performance. Consideration was given to blistering, adhesion, fouling, and cathodic-protection current requirements.

The Navy standard Formula 15 gave superior performance, although the current requirement was greater than that for most commercial resin coatings. A Saran coating, Formula 113, had excellent electrical resistance and showed no abnormal breakdown.

Continuous control of current must be maintained to prevent overpolarization and damage to a coating. A comparison between protected and unprotected panels coated with the same material and placed in the same environment indicated that pitting was eliminated and surface corrosion minimized when cathodic protection was applied. The study corroborated previous investigations of paint failure on a cathodic surface. The effect of metallic pigments on power requirements was demonstrated, as was the importance of adhesion, blistering tendency, and electrical resistance in the selection of a material to be used with cathodic protection. A systematic study of paint formulation was recommended, with the aim of developing optimum coatings for steel surfaces in contact with sea water.[9]

Figure 17. Floating test rack for paint compatibility.

Floating Corrosion Inhibitors and Cathodic Protection

Protection for the interior compartments of active floating drydocks has been a problem of long standing. At first, protection was attempted through paints or similar coatings, which were sometimes expensive and often inadequate. Recent years have seen flotation-type corrosion inhibitors applied and cathodic protection systems installed in attempts to provide continuous protection with a minimum of maintenance. Both methods have inadequacies; a floating inhibitor never reaches the entire bottom, since pumping operations would discharge it from the deck. Cathodic protection, on the other hand, is effective only in a conducting medium. It can protect to a limited degree lower bulkheads in the wet-dry zone, but upper bulkhead areas and the overhead surfaces cannot be protected by cathodic protection.

To evaluate properly the interaction of flotation-type inhibitors and cathodic protection, a small laboratory experiment was set up. Graphite and magnesium anodes were employed, with and without inhibitors, using mild steel coupons to determine the effectiveness of the several systems. The coating resulted in a 5 to 1 reduction in current requirement for the graphite system and 8 to 1 for the magnesium system. No change was made in the electrolyte, so part of the reduction in current for the magnesium system was accountable to an increased alkalinity of the fluid and the deposition of a calcareous coating on the steel coupon.

The results of the preliminary study indicated the advisability of a large-scale test. Factors to be considered were: zones of corrosion (wet, wet-dry, dry), type of inhibitor (single or two-component), and type of cathodic-protection system (galvanic or impressed). In order that the area to be protected by each combination of inhibitor and cathodic protection would be equal, six standard T6B pontoons were obtained. A pumping and piping system was supplied to simulate actual ballast tank operations. As shown in Figure 18, the pontoons were modified by the addition of inlet and outlet pipes and a sight-glass level indicator. The inlet pipe enters near the top center of one side of each pontoon, and extends through the wall and down to within 6 inches of the bottom of the pontoon. Electrical independence was insured by mounting the pontoons on wooden bases and using plastic nipples between the pontoons and the piping system.

Each pontoon had a different combination of inhibitor and cathodic protection: No. 1 contained a single-component inhibitor only, and No. 2 contained impressed current (Duriron anode) only. Numbers 3 and 4 contained impressed current (graphite anode) with single- and two-component inhibitors, respectively. No. 5 contained a galvanic (magnesium) anode and a two-component inhibitor; No. 6 contained only a two-component inhibitor.

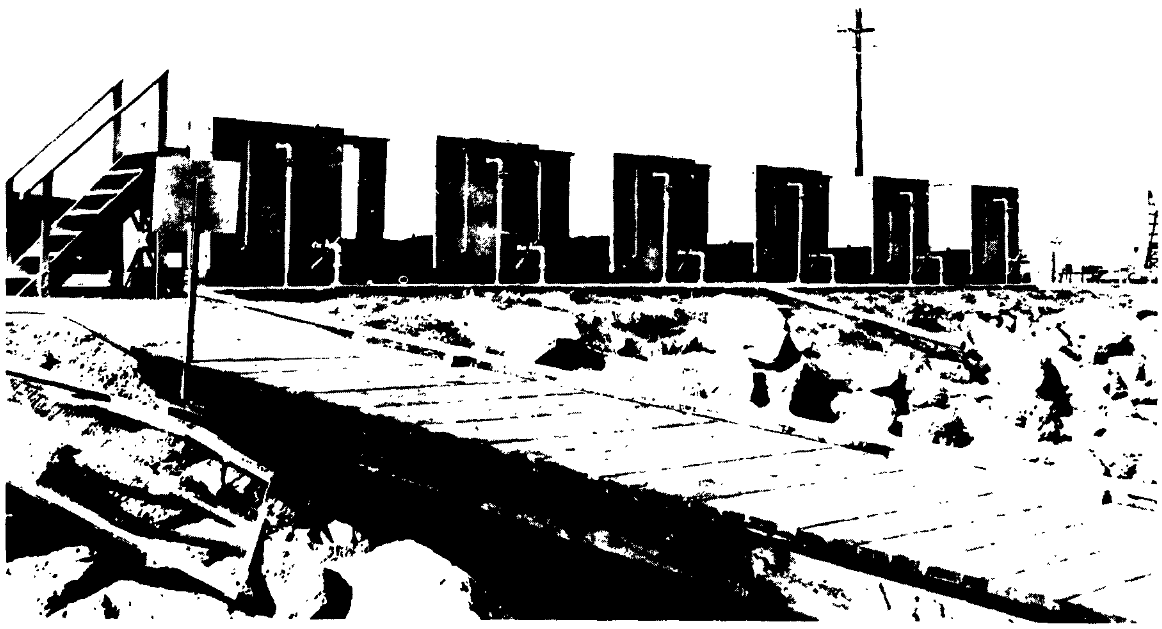


Figure 18. Floating inhibitor test facility.

A number of pre-weighed sandblasted mild steel coupons were mounted as shown in Figure 19; when the pontoon contained a cathodic protection system, one coupon of each pair was electrically insulated. The insulated coupons in Pontoon No. 2 were used for determining the corrosion rate of unprotected coupons.

After the test coupons were installed, a quantity of inhibitor (as required by the above schedule) was sprayed into the separate pontoons, followed by an injection of one foot of sea water and more inhibitor. Then the entire pontoon was filled, kept full for 10 minutes; then the water was lowered to a 16-inch depth. Next, the cathodic protection systems were energized. After 24 hours the water was raised to the top for one week and then lowered to the 16-inch depth for one week. This cycle was continued for a year, with a layer of the appropriate coating on the water surface at all times.

Potential readings were taken weekly before the water level was changed. The graphite anodes in No. 4 pontoon were twice coated with the floating inhibitor; on neither occasion was there an effect on the current discharge.

At the end of the year the test coupons were removed, electrolytically cleaned, and weighed. The corrosion rates were determined and are shown in Table II. By combining cathodic protection with a floating inhibitor the corrosion rate was reduced almost to zero. Either method alone reduced the corrosion by at least 70 percent.

In the wet-dry zone, cathodic protection by itself was only one-third as effective as in the permanently wet zone; however, use of a floating inhibitor with or without cathodic protection almost completely eliminated corrosion in the wet-dry zone. In the dry zone, cathodic protection was useless, but here too the inhibitor almost completely eliminated corrosion.[10]

YD-171 Floating Crane

The Laboratory was requested to design a cathodic protection system for the YD-171 floating crane at the Long Beach Naval Shipyard. The system was to supplement the standard ship-bottom paint system. The first installation consisted of a rectifier and control panel mounted on the hull and five 4-inch-diameter by 40-inch-long cylindrical anodes suspended over the ends and sides.

The suspension locations did not prove acceptable. The anode holders caused chafing of the manila mooring lines, and frequently the mooring lines rendered the anodes inaccessible. The necessity of raising the anodes for movement of the crane to another location, and the inconvenience of the anodes and cable lying on the deck rendered the system unsatisfactory to crane personnel.

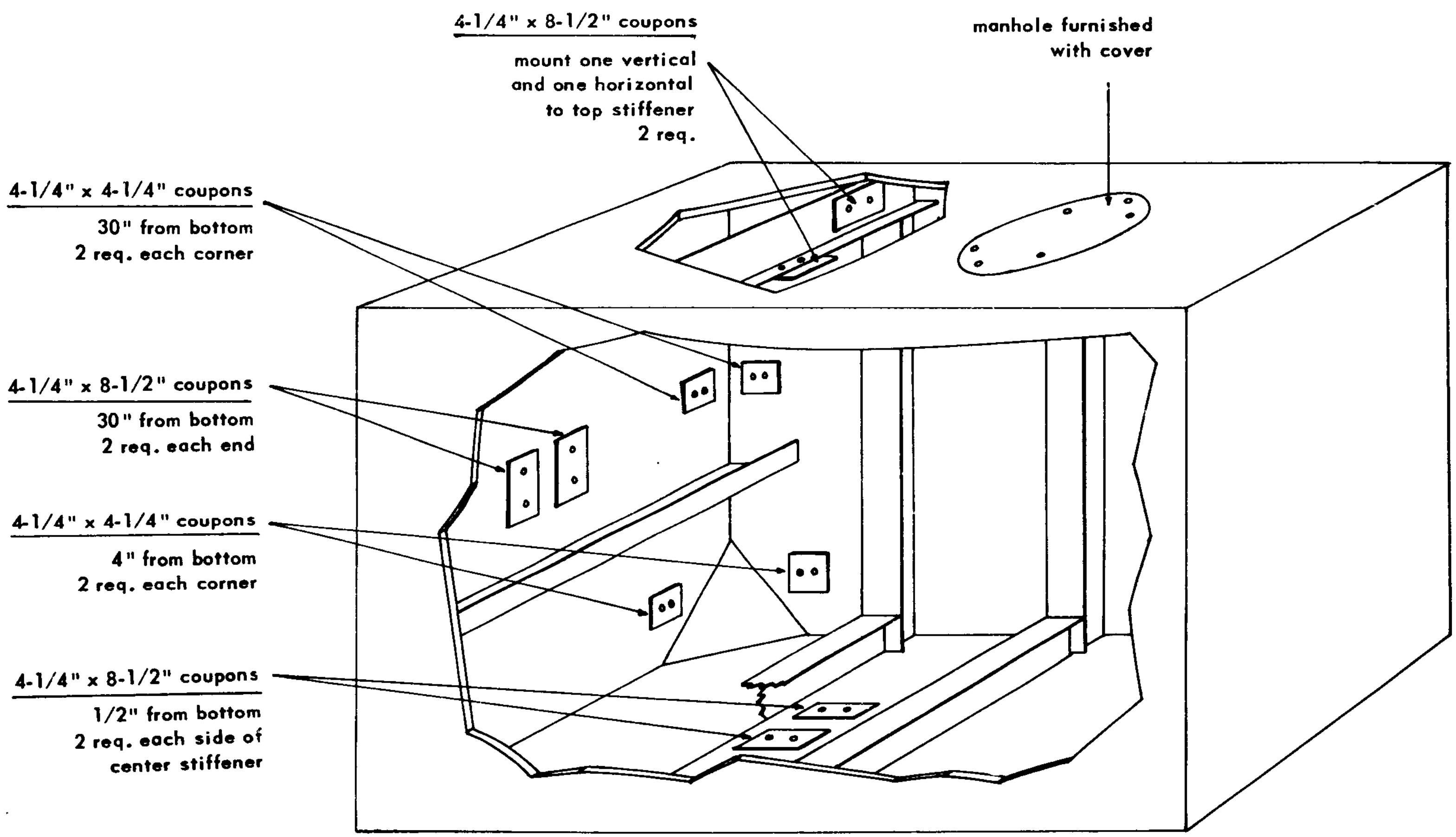


Figure 19. Cutaway of T6B pontoon showing location of test coupons.

Table II. Corrosion Rates of Test Coupons in Various Exposure Zones

Exposure	Wet Zone		Wet-and-Dry Zone		Dry Zone	
	Average Loss (mpy)*	Reduction in Corrosion Rate (percent)	Average Loss (mpy)*	Reduction in Corrosion Rate (percent)	Average Loss (mpy)*	Reduction in Corrosion Rate (percent)
Sea Water (control)	3.0	**	8.14	**	7.02	**
Cathodic Protection	0.839	72.2	5.33	34.5	7.02	0.0
Type I Inhibitor	0.411	86.3	0.151	97.2	0.108	98.5
Type I Inhibitor with Cathodic Protection	0.088	97.1	0.122	98.4	no data	no data
Type II Inhibitor	0.325	89.1	0.108	98.7	0.028	99.7
Type II Inhibitor with Cathodic Protection	0.093	97.0	0.147	97.3	no data	no data

* Mils per year (inches per year multiplied by 10^{-3}

** Insulated coupons used for determining reduction in corrosion rate

As a result the system was redesigned to provide eight rectangular (3-inch by 6-inch by 30-inch) anodes in holders made of laminated insulating board and mounted directly on the hull. An instruction manual[11] was written as a guide for personnel operating and maintaining the system. The permanent attachment of the anodes eliminated part of the difficulty, but the lead wires were subject to damage from camel logs, floating debris, and traffic on the deck. Finally the system was redesigned to retain the hull-mounted anodes, but to allow the lead wires to penetrate the hull through stuffing boxes located near the anodes. Inside the compartments the leads were run through conduit until they were well above the interior waterline. Where possible the anode leads followed existing wiring to reach the rectifier.

In its present design, the system should require little more than periodic potential determinations around the hull, followed by necessary adjustments in the amount of current to each pair of anodes.

DISCUSSION

These studies have demonstrated that cathodic protection can minimize the corrosion of steel in sea water. The apparent difference in effectiveness of the several types of systems and anode materials studies can be accounted for to a large degree by the differences in control methods and experimentation within a system, as well as the difficulty of insuring steady electrical continuity throughout a system.

The AFDL-12 system initially required 8 amperes for satisfactory protection; during the three ensuing years as much as 13 amperes was carried by the single anode. The latter value is almost four times the maximum current recommended for the size anode used. Accelerated deterioration of the anode would be expected under such conditions, and was found to be the case. After three years the single anode had lost 15 percent of its original weight and was soft and porous. Despite this excessive deterioration the anode functioned satisfactorily up to the time of inspection.

Table I shows a difference in weight loss between the protected AFDL-20 coupons which is not reflected by the unprotected coupons. The reason for this may be that, for 6-1/2 months, coupon 2 was almost the full length of the dock away from the protecting anode, while coupon 1 was only the width of the dock away. It is not known whether the different circuit-lengths between the anode and the coupons affected the corrosion rate. The AFDL-20 was an active drydock and, as the dock was lowered, more area would require protection from the single anode. The increased area and the limits of the anode's protecting range may have placed the more remote coupons outside the safe area part of the time.

Costs have been estimated for three different systems for protecting an AFDL-class floating drydock. The magnesium system would cost $285 for five years, whereas the graphite system would cost $420 for the same period. The zinc anode system would cost $220 for two years if the extra cable and accessories required by the experimental nature of the installation were eliminated. Both the magnesium and zinc systems would be completely expended during their respective periods, but components of the graphite system would have a residual value of about $200.

On a per-year basis, the graphite system would cost $44, magnesium $57, and zinc $110. Not included in these estimates are the man-hours for installation and monitoring as required by the graphite and magnesium systems, or the variable resistances which the magnesium system requires for greatest efficiency. All items required to provide a satisfactory system have been covered in the estimate for the zinc system. Although the graphite system has a good lead over the other two, the final decision will depend on a balance between maintenance convenience and average cost.

The need for protecting the interiors of active floating drydocks is perennial. To help satisfy this need, the floating inhibitor-cathodic protection compatibility study was made. Certain procedural differences between Laboratory and field practice should be noted. In the NCEL study, the water level of the simulated ballast tanks was raised at a relatively slow, steady rate, and the high and low levels were each maintained for one week. A selection such as this was necessary to provide an operation as standardized as possible.

In actual practice, operators raise and lower drydocks as fast as possible. Ballast tanks are empty for much longer periods than they are full. Furthermore, when drydocks are raised rapidly, part of the floating inhibitor is pumped overboard. The layer of material which manufacturers say should always be on the surface of the ballast water is seldom there. As a consequence the results obtained in the NCEL study may be somewhat idealized when compared to those obtained from coupons used in an actual installation. However, they are valuable in establishing the effectiveness of cathodic protection and floating inhibitors.

The inspection of the YFD-70 revealed that certain areas may never have come in contact with any of the corrosion inhibitors, or that heat may have caused the inhibitor to flow. A corrosion-inhibiting material which would not flow under the temperatures encountered in practice could be of great benefit in mitigating the corrosion on the warmer surfaces of active floating drydocks.

Frequently articles are written about cathodic protection applications on ships, sea walls, piers, and other structures in a sea water environment. Usually an estimated life in years is mentioned, but follow-up articles on the systems seldom if ever appear. As a result there exists much published data on the design of cathodic protection installations for sea water locations, but little information on how such systems have actually performed.

The AFDB-4 installation was expected to provide a documented study of the effectiveness of cathodic protection over a long period. It has already been noted that fiscal limitations eliminated the scheduled drydocking of several AFDB sections, but it is felt that continued attention should be given to this structure. If the sections were drydocked, it would be possible to obtain data which could fill another of the gaps in existing knowledge.

CONCLUSIONS

1. Impressed current (graphite anode) and galvanic (zinc or magnesium) anode cathodic protection systems are effective in reducing the corrosion of interior and exterior steel surfaces in sea water. High-purity (low iron) zinc anodes are preferable where maintenance is difficult or manpower is not readily available. Magnesium anodes are equally acceptable where a steady power supply is not readily available, and where some maintenance time can be used. Graphite anode systems are acceptable for most uses when a reliable power supply is readily available.

Impressed current or magnesium anode systems may be used in ballast tanks if a two-component floating corrosion inhibitor is also to be used, but only if the necessary control cables are unaffected by the inhibitor. Zinc anodes are to be preferred for such installations.

2. Properly applied corrosion inhibitors and cathodic protection will appreciably reduce the corrosion of ballast tanks.

3. Automatic control systems can effectively maintain uniform polarization in impressed-current cathodic-protection systems.

4. Several standard Navy paint systems are shown to be compatible with cathodic protection for at least one year, which was the duration of the study.

RECOMMENDATIONS

1. Paint systems for underwater application should be investigated further for their compatibility with cathodic protection. A standard Navy paint system which incorporates Formula 15 antifouling paint is recommended for use with cathodic protection systems.

2. Corrosion inhibitors should be used in all active drydocks concurrently with cathodic protection.

3. Development of automatic controls for single- and multiple-hull installations should be continued.

4. Current and polarization records on the AFDB-4 should be maintained. In order to obtain desirable data, hydrostone molds should be made, photographs should be taken, and all steel coupons should be retrieved when any sections are drydocked.

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